

फल और सब्जियों के लिए सौर ऊर्जा संचालित वाष्पीकृत शीत ग्रामीण
भंडारण गृह का विकास

**DEVELOPMENT OF SOLAR POWERED EVAPORATIVE
COOLED RURAL STORAGE STRUCTURE FOR FRUITS AND
VEGETABLES**

SHEKH MUKHTAR MANSURI



**DIVISION OF AGRICULTURAL ENGINEERING
INDIAN AGRICULTURAL RESEARCH INSTITUTE
NEW DELHI -110 012**

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**DEVELOPMENT OF SOLAR POWERED EVAPORATIVE
COOLED RURAL STORAGE STRUCTURE FOR FRUITS AND
VEGETABLES**

A Thesis

By

SHEKH MUKHTAR MANSURI

Submitted to the Faculty of Post-Graduate School,
Indian Agricultural Research Institute, New Delhi
in partial fulfillment of the requirements
for the award of the degree of

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This is to certify that the thesis entitled, **“Development of Solar powered Evaporative cooled rural storage structure for fruits and vegetables”**, submitted to the Faculty of the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfillment of the requirements for the degree of **MASTER OF TECHNOLOGY in AGRICULTURAL ENGINEERING** is a record of *bona fide* research work carried out by **SHEKH MUKHTAR MANSURI, Roll No.-20376** under my guidance and supervision, and no part of this thesis has been submitted for any other degree or diploma.

It is further certified that all the assistance and help availed during the course of investigation as well as all sources of information have been duly acknowledged by him.

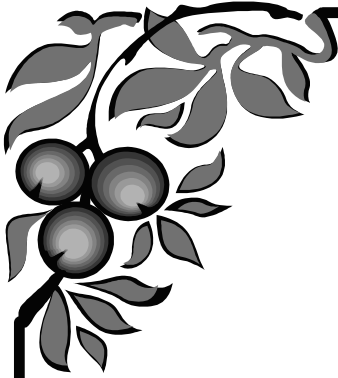
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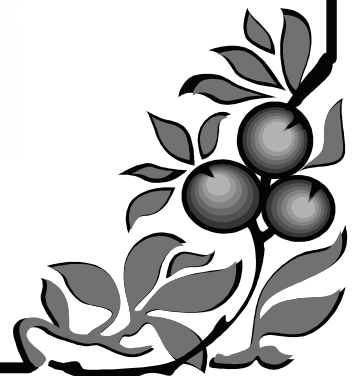


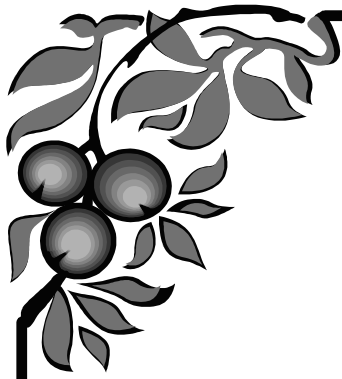
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My Beloved
family members. . . .





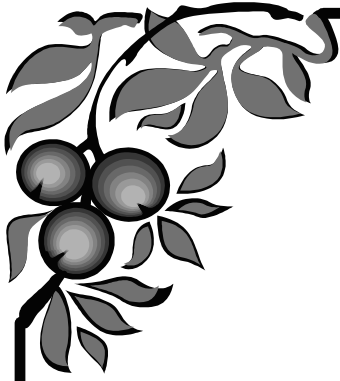
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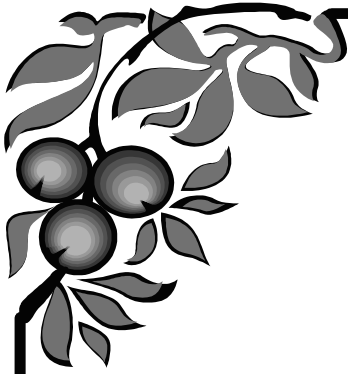
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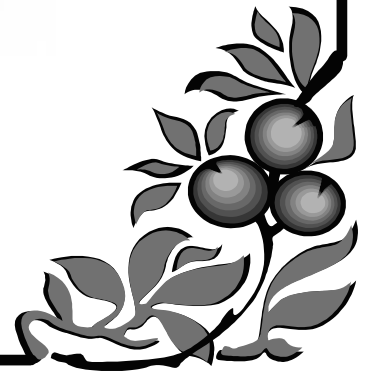


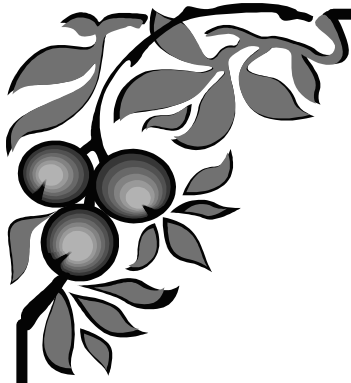
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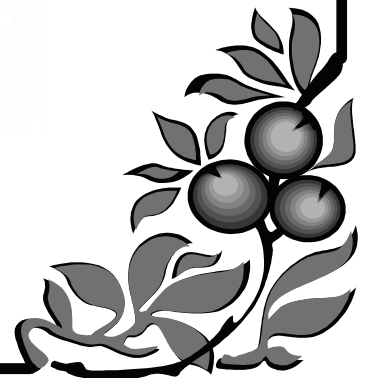


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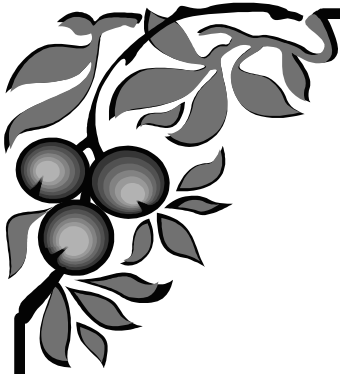
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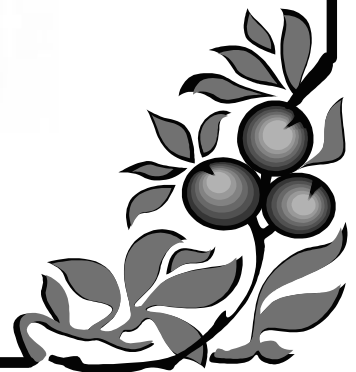


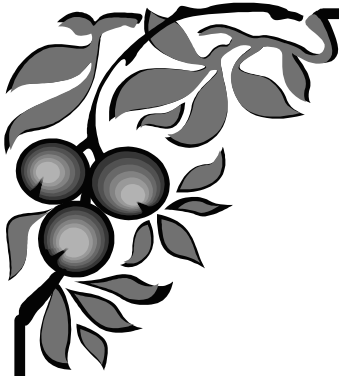
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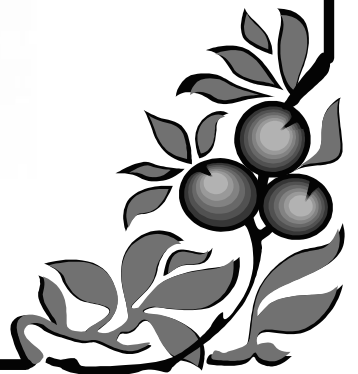


Introduction





Discussion



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“Research is what I’m doing when I don’t know what I’m doing”

“The best and safest thing to keep a balance in your life, acknowledge the great powers around us and in us. So, it is essential that I acknowledge the great powers, who paved the way on which I have walked so far. Any accomplishment requires the effect of many people along with the sincere guidance of experienced persons and blessings of God and this work is not different.”

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Place: New Delhi

CONTENTS

CHAPTER	TITLE	Page No.
I	INTRODUCTION	1-4
II	REVIEW OF LITERATURE	5-21
III	MATERIAL AND METHODS	22-44
IV	RESULTS	45-62
V	DISCUSSION	63-65
VI	SUMMARY AND CONCLUSIONS	66-67
VII	ABSTRACT (ENGLISH)	68
VIII	ABSTRACT (HINDI)	69
	BIBLIOGRAPHY	i-viii
	APPENDICES	a-g

LIST OF TABLES

TABLE NO.	TITLE	Page No.
2.1	Recommended temperature, relative humidity and shelf life	11
3.1	Conductive heat gain of ECSS	27
3.2	Design layout of RCBD experiment to assess the cooling efficiency for selection of suitable material	43
3.3	Design layout of RCBD experiment to assess the performance of ECSS	44
4.1	ANOVA	53
4.2	Cooling efficiency with different pad area	53
4.3	Cooling efficiency with different pad materials	54
4.4	Effectiveness data of the evaporative cooler	54
4.5	Effect of ECSS on PLW (%)	56
4.6	Effect of ECSS on Firmness (N)	59
4.7	Effect of ECSS on color	60
4.8	Change in Shelf-life (in days) of fruits and vegetables when stored in ECSS and in room	62

LIST OF FIGURES

FIGURE NO.	TITLE	Page No.
3.1	Floor diagram of ECSS	25
4.1	Hourly variation of solar intensity on horizontal surface and at tilt (panel)	47
4.2	Hourly variation of voltage and current	47
4.3	Hourly variation of solar intensity and Solar PV system power	47
4.4	Hourly variation of temperature (a) and relative humidity for ambient and inside the ECSS when pad was used at one side	48
4.5	Hourly variation of temperature (a) and relative humidity for ambient and inside the ECSS when pad was used at two sides	49
4.6	Hourly variation of temperature (a) and relative humidity for ambient and inside the ECSS when pad was used at three sides	50
4.7	Hourly variation of temperature (a) and relative humidity for ambient and inside the ECSS when pad was used at four sides	51
4.8	Hourly variation of saturation efficiency for three different pad material (a, b, c) when pad used one, two, three and four side in each of the material	52
4.9	Hourly variation of temperature (°C) during storage of fruits and vegetables in ECSS and in ambient	57
4.10	Hourly variation of relative humidity (%) during storage of fruits and vegetables in ECSS and in ambient	57
4.11	The changes in physiological loss in weight (%) of different fruits and vegetables during storage	58
4.12	The changes in Firmness (N) of different fruits and vegetables during storage	60

LIST OF PLATES

CHAPTER	TITLE	Page No.
3.1	Component of ECSS	34
3.2	Pad material used	35
3.3	Solar PV system	35
3.4	Instrument used for measurement	36
3.5	Evaporative cooled storage structure	37

LIST OF ABBREVIATION

±	Plus Or Minus
ANOVA	Analysis of Variance
yr	Year
mm	Millimetre
cm	Centimetre
m	Meter
g	Gram
kg	Kilogram
Fig.	Figure
h	Hour
N	Newton
<i>i.e.</i>	That is
IARI	Indian Agricultural Research Institute
kJ	Kilojoules
W	Watt
GI	Galvanized iron
MS	Mild Steel
%	Per cent
FAO	Food and Agricultural Organization

s	Second
min	Minute
A	Area
V	Volume
V	Volt
RPM	Revolution per minute
DC	direct current
AC	Alternate current
°	Degree
C	Celsius
K	Kelvin
PV	photo voltaic
W	Watt
Eqn.	Equation
l	Litre
Viz.	Namely

CHAPTER I

INTRODUCTION

In India, energy demand is being increased with increase in population and living standards. Therefore there is a need to expand access to energy in new ways. Renewable energy can make to energy autonomy, environment change relief, rural development, improved health and lower health costs (linked to air contamination). For small-scale farmers, the increasing expense and inaccessibility of electricity based farming inputs has put them under increased pressure. The majority of the efforts to increase the production of small-scale farmers have focused on distinctive energy sources. The availability of energy is a key variable for farmers who want to expand their agricultural exercises. In this circumstance, farmers may be keen to adopt farming systems which are not reliant on fossil fuels, but rather get their energy from renewable sources. The structure of energy use in Indian agriculture has changed significantly, with a critical shift from the animal and human force towards machines power, electricity, diesel and now renewable energy sources.

India is densely populated and has high solar insolation, a perfect combination for using sunlight based power in India. As indicated by a 2011 report by BRIDGE TO INDIA and GTM (Greentech Media) Research, India is confronting a perfect storm of variables that will drive solar photovoltaic (SPV) selection at a "furious pace over the next five years and beyond". With around 300 clear, sunny days in a year, India's hypothetical solar power reception, on only its territory range is about 5000 Petawatt-hours per year (PWh/yr). The daily average solar energy incident over India fluctuates from 4 to 7 kWh/m² with around 1,500–2,000 daylight hours per year (depending upon location), which is significantly more than current total energy utilization. Innovative breakthroughs for cost-effective photovoltaic technology lately have made the solar energy of high utility (MNRE, 2013).

India's assorted atmosphere ensures availability of all varieties of fresh fruits & vegetables. It ranks second in fruits and vegetables production in the world, after China. According to National Horticulture Database distributed by National Horticulture Board, during 2012-13, India produced 81.285 million tonnes of fruits and 162.19 million

tonnes of vegetables. The area under cultivation of fruits stood at 6.98 million hectares while vegetables were cultivated in 9.21 million hectares. Fruits and vegetables are responsible for 92.3 per cent of total horticultural production. However, around 2.1% production is used by processing industries; the remaining produce is either consumed soon after harvest or stored for later use in fresh form. It is important for effective exploitation of the export capability of fruits and vegetables.

Since, fruits and vegetables are very perishable, the magnitude of loss in fruits and vegetables are estimated at 35-40% due to outrageous Post Harvest Management (PHM) (XI Planning Commission). It amounts to a loss estimated at ₹ 40,000 crores each year. This is not just loss of produce of crores of rupees additionally wastage of work, energy and inputs also. India wastes fruits and vegetables every year equivalent to the annual consumption of the United Kingdom.

The impact of absence of sufficient storage facilities for fruits and vegetables after being harvested leads to the reduction in the quantity of fruits and vegetables that get to the market which also has an immediate impact on the distribution and consumption of the required amount for the sound living.

The most imperative components influencing the postharvest life and quality of horticultural produce are temperature and relative humidity. Produce quality loss after harvest happens as a result of physical, biochemical, physiological and biological procedures, the rates of which are influenced primarily by product temperature at harvesting and relative humidity surrounding the produce. The rate of spoilage increases by 2 or 3 folds with each increment in temperature of 10°C. The vital activities of the tissues, for example, transpiration, respiration and ripening etc., proceed with even after harvest. The high moisture content of the horticultural commodities accelerates the reaction response making them highly perishable. Reducing the moisture content of the commodity to a recommended level through drying or dehydration, could improve the shelf life, in spite of the fact it disturbs the general texture and impairs the quality. Fresh produce needs low temperature and high relative humidity during storage. As the maintenance of business quality is key to the success of the horticultural industry, it is therefore, not only important to cool the product down as well as to do so as quickly as possible after harvest. At the point when harvesting produce at high temperatures or at

an advanced stage of maturity, immediate cooling is important to minimize quality losses.

Refrigerated storage, which is accepted to be the best system for storing the fruits and vegetables in fresh form, is not only energy intensive but also includes enormous capital. In addition, it is not suitable for rural or on-farm storage where the producer would like to store the commodities for only a few days to accumulate sufficient quantities before conveying them to the markets situated far off and in urban regions. Power availability and its cost are additionally major issues, due to which the refrigerated storages for on-farm short duration storage are not recommended. Hence, there is a shift in accentuation in cold storage to other alternative storage systems. An alternative to maintain lower temperature in an enclosed chamber has been a matter of prime significance under Indian condition. Evaporatively cooled storage is one such alternative system that has been studied broadly.

Evaporative cooling has enormous applications, ranging from comfort cooling in private, business, agricultural and institutional buildings to modern applications, for example, spot cooling in power plants, foundries and so forth (ASHRAE, 2003). This rule is mainly utilized in greenhouses. Evaporative cooling is a physical phenomenon where cooling of an object or a fluid occurs because of evaporation of a liquid into surrounding air which is in contact with it. Evaporation of water creates an impressive cooling impact and the faster the evaporation the more prominent is the cooling. Evaporative cooling is valuable for short term storage of fruit and vegetables. It is efficient and economical for temperature reduction and increasing relative humidity, is a tried and tested system, is environmental friendly and does not require special skills to operate. In this way evaporative cooling could be seen as an alternative to address postharvest losses in fresh produce suffered by farmers in India if less expensive energy sources to power the cooling system, utilizing local available material can be found.

The evaporative cooled storage structure has turned out to be useful for short term, on-farm storage of fruits and vegetables in hot and dry regions. Evaporative cooling is an efficient and economical means for reducing temperature and increasing the relative humidity of an enclosure, and has been extensively tried for improving the shelf life of horticultural produce which is essential for maintaining the freshness of the

commodities. Evaporative cooling is an environmental friendly air conditioning system that works utilizing induced processes of heat and mass transfer where air and water are working fluids. Such a system provides an inexpensive, energy efficient, environmentally benign (not require ozone damaging gas as in dynamic systems) and potentially attractive cooling system.

In the light of above facts, solar energy can be a decent alternative and efficient energy source that can substitute the non-renewable energy sources with greater reliability. Considering the specifics the present research work for developing solar energy powered rural storage structure for fruits and vegetables is undertaken with the following objectives:

- I. To design and fabricate a solar powered evaporative cooled storage structure.
- II. To evaluate the performance of storage structure for storing selected fruits and vegetables.

CHAPTER II

REVIEW OF LITERATURE

Storage of fruits and vegetables in cold storage has been a critical area of research because at low temperature, these perishable commodities can be preserved in their wholesome state for longer periods. This is accomplished through hindrance of changes in metabolic activities viz. respiration rate, activities of the micro-organisms and enzymes etc. However the absence of cold storage facilities to accommodate ever increasing supply of fruits and vegetables has compelled the producers to adopt alternative storage practices; practices that in effect would preferably be economical than the expense of renting space in cold store and more efficient than rustic storage producers (Dahiya *et al.*, 1997b). Therefore, evaporative cooled storage structure which can maintain lower temperature coupled with high humidity; provide enough guarantees for short-term storage of horticulture produce.

2.1 Role of horticultural crops in human nutrition

Horticulture sector comprising a wide array of produce from fruits and vegetables to nuts, spices, medicinal plants, flowers, and plantation crops, provides various opportunities for income generation. Globally India is the second largest producer of fruits and vegetables; the largest producer of mango, banana, coconut, papaya, cashew, and pomegranate; and the largest producer and exporter of spices. Horticulture production, estimated at 265 million tonnes, surpassed the production of food-grains and oilseeds in 2012-13, owing to an 8.6 per cent increment in productivity of horticulture crops between 2008-09 and 2012-13.

From human nutrition perspective horticulture is most important to our daily living. Fruits and vegetables are the chief sources of carbohydrates, vitamins, minerals, fats, proteins etc. Fruits and vegetables are perceived as protective foods as they are necessary for the maintenance of human health. The per capita availability of fruits increased from 114 g per day in 2001-02 to 172 g per day in 2011-12; while that of vegetables increased from 236 g per day to 350 g per day over the same period. Substantial enhancements in per capita availability levels are required to wipe out hunger in India.

2.2 Postharvest Losses

Huge post-harvest losses of fruits and vegetables are a matter of severe alarm toward India's agriculture area. Yet, this is a general sensation and it is occurring in almost each of developing nations and this as well used to take place in developed nation too. Fruit and vegetables require proper postharvest management to maintain quality and decrease losses. The susceptibility of perishable products during storage and distribution is the primary cause of postharvest losses in the tropical and sub-tropical regions (Ngcobo *et al.*, 2012). Workneh (2007) claims that postharvest losses could discourage farmers from venturing into production and marketing of fresh produce and thus influencing the supply side of utilization of fruit and vegetables in urban areas. Accordingly, reduction of postharvest losses, especially if it can economically be avoided, would be of great significance to farmers and consumers (Johnson and Sanghote, 1994).

Fruit and vegetables are highly perishable and if not properly handled at their optimum conditions after harvesting or during packaging or transportation; they easily deteriorate and become unsuitable for consumption (Verma and Joshi, 2000). As indicated by Kitinoja *et al.* (2010) the world over postharvest losses are estimated at an average of 30-40% in fruit and vegetables before they reach the final consumer. Globally average postharvest losses in general for fresh produce are estimated at 30%. Basediya *et al.* (2011) reported that postharvest losses of fruit and vegetables in India went from 30 to 35%.

2.3 Causes of Postharvest Losses

Postharvest losses occur as an effect of many factors that incorporate environmental, biological, chemical as well as technical factors (Kader, 1986). Fruit and vegetables are also affected by environmental factors of gas composition, temperature and relative humidity. Most fruit and vegetables have moisture contents higher than 80% and encounter high respiration rate. Also their texture is delicate and does not withstand impact and brutal environmental conditions. Technical factors that result in postharvest losses incorporate mechanical/physical damage due to improper handling (Adeoye *et al.*, 2009; Vigneault *et al.*, 2009; Basediya *et al.*, 2011) or absence of skill in the use of appropriate technology designed for keeping ideal state of perishable produces.

Physiological and biological processes cause evaporation of water from produce, bringing about chemical and physical changes of fruit and vegetables (Brosnan and Sun, 2001; Pathare *et al.*, 2012).

Mechanical damage as a consequence of the factors increases moisture loss from the produce. The rate of moisture loss may be increased by four times as a result of a single bad bruise on surface of an apple, and weight loss in skinned potatoes may be 300 to 400 percent as much as non-skinned potatoes (Wilson *et al.*, 1999). Injuries resulting from mechanical damage such as bruising, surface abrasions and cuts can also quicken the loss of vitamin C in fruit and vegetables. Therefore, fruit and vegetables targeted for storage should be absolved of any skin abrasions, bruises, spots, rots, decay or any mechanical harm. To ensure that mechanical damage is isolated or possibly minimized appropriate technique of harvesting, handling and air-cooling with humidification should be applied (Wills *et al.*, 1998).

2.3.1 Technical Factors

The technical factors that influence produce quality are mainly associated with occurrence of mechanical damage or injury to fruit and vegetables (Prusky, 2011), absence of skilled manpower in technical aspects of how to handle fresh commodities and increased storage time (Wilson *et al.*, 1999). Fresh produce response to mechanical stress relies upon time (Wang and Chang, 1970) referred to here as “long storage time” and the longer the duration the higher the mechanical stress.

2.3.2 Biological Factors

Fresh produce are living respiring tissues even after they have been isolated from the mother plant during harvesting they continue to transpire, respire and further ripen (Ngcobo *et al.*, 2012). These metabolism processes cause loss of moisture from produce which is not replaced and this can prompt to senescence or total death (Booth, 1974). The physiological decay due to respiration, transpiration and biosynthesis is affected by environmental factors of temperature, relative humidity and gas composition, which can bring about a huge loss of nutritional value and in many cases the whole fruit or vegetable is lost (Joas and Lechaudel, 2008).

Chemical and enzymatic changes also occur in fresh produce causing tissue softening, pigmentation loss, off colouring and off-flavour advancement bringing about postharvest losses (Brosnan and Sun, 2001). In general, physiological, chemical and enzymatic changes are explored when fresh produce is subjected to ambient temperature during storage and transportation. Despite this knowledge by many small scale farmers in the developing nation fruit and vegetables are transported to local commercial centers without controlling the surrounding temperature and relative humidity (Nunes, 2009).

2.3.3 Environmental Factors

As indicated by Nunes *et al.* (2009) and Choudhury (2005), temperature and relative humidity are the two most important environmental factors influencing the quality and the storage life of fresh produce. Jain (2007) incorporates the gas composition surrounding the produce as an environmental factor that directly affects storage life of fruit and vegetables. Proper storage and transport practices of fruit and vegetables include control of temperature and relative humidity, air flow and maintenance of space between containers for satisfactory ventilation (Basediya *et al.*, 2011). The storage life of a product differs with species, variety and pre-harvest conditions particularly quality and maturity. Impressive amounts of fresh produce are lost before it reaches the market due to failure by farmers to regulate temperature and relative humidity during storage and transportation. Maintenance of fresh produce quality requires correct application of optimum temperatures and relative humidity from harvest to the consumer (Paull, 1999; Zude, 2009) and these variables are henceforth a genuine thought of this study.

2.3.3.1 Effect of temperature on post harvest losses

Deterioration of fruit and vegetables during storage and transportation is generally affected by temperature (Getinet *et al.*, 2008; Vigneault *et al.*, 2009; Pathare *et al.*, 2012). As per Lee and Kader (2000), temperature management after harvest is the most important variable to keep up supplements including vitamins of fruit and vegetables. It is also known that postharvest losses are quickened at higher temperatures and with longer storage durations. Respiration rate, metabolic processes and ethylene biosynthesis of some fruit increase with air/room temperature within a given extent.

Respiration rates can double, triple or even quadruple with each increment in temperature (Zagory and Kadar, 1988). High temperatures accelerate physiological decay and senescence as fruit rot organisms spread most quickly at warm harvest temperatures (Brosnan and Sun, 2001; Sandhya, 2010).

The mechanism of containing fruit physiological deterioration through directed temperature management is the control of the crop's respiration rate (Kader, 1986). Respiration creates heat as sugars, fats, and proteins in the cells of the crop are oxidized. The loss of these stored food reserves through respiration means diminished food value, loss of flavor, loss of salable weight, and fast deterioration. The respiration rate of a product strongly decides its transit and postharvest life. The respiration rate will be higher for the higher storage temperature (Wilson *et al.*, 1999; Sandhya, 2010).

The storage of fruit and vegetables at low temperature instantly after harvesting will reduce the rate of decomposition and microbial decay. The low temperature helps in maintenance of quality and freshness of the stored material for a longer period. Fresh produce shelf life can double by reducing temperature from 10°C to 5°C. Generally, the storage temperature of fruit and vegetables is 0°C to 12°C and most tropical and subtropical fruit require high temperatures of 5°C to 12°C or to 13°C as indicated by (Barbosa, 2007) else they endure chilling injury. Therefore, vegetables must be classified according to whether they are susceptible to cold temperatures like carrots, potatoes, bananas. To accomplish these recommended temperatures, produce must be pre-cooled.

The process of pre-cooling is the removal of field heat quickly after harvest to capture the decay and senescence process. Precooling can be achieved through distinctive methods that include forced air cooling, vacuum cooling, hydro-cooling and evaporative cooling (Tigist *et al.*, 2011). Pre-cooling, thus, helps achieve prescribed storage temperatures for fresh produce and thus ensuring maintenance of high level quality that meets customers fulfillment (Brosnan and Sun, 2001). Generally, the ideal storage temperature for fruit and vegetables at the temperature range of 5°C to 12°C is achievable by most cooling technologies including adiabatic evaporative cooling. Adiabatic evaporative cooling is regarded as most reduced capital investment (Tigist *et al.*, 2011).

As per Basediya *et al.* (2011), if the surrounding air temperature is decreased to create storage at optimum levels within four hours, the following are achieved; produce respiration rate is decreased; reduction of water loss from produce; concealment of ethylene production, and significant reduction of the development of microbial activity.

2.3.3.2 Effect of relative humidity on post harvest losses

Relative humidity is another essential aspect that is considered during handling of fruit and vegetables under a controlled environment (Prusky, 2011). In low relative humidity, the air is holding only a little amount of the total possible quantity of water vapour it can hold. In these situations the air can take in more moisture causing produce to increase transpiration rate (Getinet *et al.*, 2008). Then again, when the relative humidity is high, the rate of water evaporation is low, and likewise cooling is also low. This infers that there is need for regulated storage and transportation conditions of fresh produce.

Hardenburg *et al.*, (1986) presumed that regulated storage or transportation conditions retard the following components of deterioration in perishable crops:

- Aging because of ripening, softening, and textural and color changes
- Undesirable metabolic changes and respiratory heat generation
- Moisture loss and the wilting that result
- Spoilage because of attack by bacteria, fungi, and yeasts and
- Undesirable growth, for example, sprouting of potatoes

Cooling has been recognized historically as a cold chain management tool to provide controlled environment for fresh produce (Ngcobo *et al.*, 2012). There is therefore, a need to create appropriate cooling facility that is moderate and that compares well with the routine refrigeration system (Basediya *et al.*, 2011). Among the critical issues to be researched with this proposed appropriate cooling facility is whether it will build relative humidity to the required optimum levels. It is also important to attempt a cost benefit analysis of the introduction of such a technology versus routine refrigeration.

Optimum temperature (°C) and relative humidity as (%) for selected produce specific to India with present or future commercial benefits are given in Table 2.1.

Table 2.1 Recommended temperature, relative humidity and shelf life

S. No.	Product		Optimal storage temperature (°C)	Optimal relative humidity (%)	Shelf life
1	Banana	Green	17-21	85-90	1 week
		Ripe	13-16	85-95	< 1 week
2	Grapes		0	85	2-4 days
3	Guava		7-10	90-95	3-4 days
4	Mango		10-13	85-95	2-3 weeks
5	Oranges		4-7	90-95	4-6 days
6	Spinach		0	95-100	4-6 days
7	Straw berries		0	90-95	1-2 days
8	Tomatoes		13-21	90-95	4-7 days

2.4 Evaporatively cooled storage structure (ECSS)

In India hot and dry weather prevails for a noteworthy part of the year. Surrounding hot and dry weather is suitable for efficiently working of the ECSS (Jha and Chopra, 2006; Vala and Joshi, 2010). Perishable farming produce can be safely stored in ECSS. Utilization of evaporative cooling concept in storage of agricultural produce may be one alternate as it can be used for transient on-farm storage of perishables as well as for pre-cooling of fruits and vegetables before transit and storage in cold storage. Evaporative cooling is the simplest and economic method for extending shelf life of fruits and vegetables and can also be used as ripening chamber for banana (Jha, 2008; Okunade and Ibrahim, 2011).

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, commonly into surrounding air, cools an object or a fluid in contact with it. When considering water evaporating into air, the wet-bulb temperature, when compared with the air's dry-bulb temperature, is a measure of the potential for evaporative cooling. The greater the temperatures difference greater the evaporative cooling effect. Theoretically, the lowest temperature that can be accomplished by the evaporation of water is the wet bulb temperature of mist air (Hall, 1975). Evaporation of water creates a considerable cooling effect and the effect increases with increase in the amount of evaporation

(Esmay and Dixon, 1986). The principle of working of this system is ‘when a particular space is conditioned and maintained at a temperature lower than the ambient temperature surrounding the space, there should be arrival of some moisture from outside the body’. This maintains low temperature and high humidity in the space compared to the surrounding. This evaporative cool chamber satisfies all these requirements and is useful to small farmers in rural areas (Dadhich *et al.*, 2008).

Cooling is given by the evaporative heat exchange which exploits advantage of the principles of the latent heat of evaporation where tremendous heat is exchanged when water evaporates. It makes utilization of the free latent energy in the atmosphere. For an ideal evaporative cooler, which implies, 100% efficient, the dry bulb temperature and dew point should be equivalent to the wet bulb temperature (Camargo, 2007).

2.4.1 ECSS of fruits and vegetables

FAO (1983) advocated a low cost storage system based on the principle of ECSS of fruits and vegetables, which is simple, and generally effective. The essential principle relies on cooling by evaporation. However, sometimes when evaporative cooling system is utilized in preservation, it is utilized with shade on top (Kittas *et al.*, 2003).

Sushmita *et al.*, (2008) did a research on Comparative Study on Storage of Fruits and Vegetables in ECSS and in Ambient. An evaporative cool chamber was built with the help of baked bricks and riverbed sand. It was recorded that weight loss of fruits and vegetables kept inside the chamber was lower than those kept outside chamber. The fruits and vegetables were fresh up to 3 to 5 days more inside than the outside chamber.

Numerous researchers carried out its efficacy for increasing shelf-life of fruits and vegetables namely; tomato, potato, mango, grapes, orange, banana, plums, aonla, bitter gourd, capsicum, cauliflower, pineapple, peach, green pepper, cluster bean, brinjal, cucumber, chili, ladies finger, beat, peas, carrot, radish and leafy vegetables (Ganesan *et al.*, 2004; Jha, 2008; Kumar and Nath, 1993; Mishra *et al.*, 2009; Roy and Khurdiya, 1986; Singh *et al.*, 1998; Singh and Satapathy, 2006; Samira *et al.*, 2011). They also built various sizes ECSS using different construction materials. The capacity of ECSS varies from few kg to few tonnes. Some researchers also evaluated ECSS utilizing various pad materials, environment parameters, operational parameters, produce parameters for temperature drop and relative humidity. The distributed data on all the

above was reviewed; namely structural parameters, pad materials, operating parameters and performance in terms of shelf-life of farm produce.

2.4.2 Advances in evaporative cooling

Abdalla *et al.*, (1995) worked with the advancement of a fan driven evaporative cooler. The research was to study the suitability of utilizing palm leaves as a wetted medium. This research was made conceivable due to the availability of palm leaves in Saudi Arabia. According to the research it was claimed that palm leaves could be utilized as the wetted media which is locally available to the masses.

Sanni, (1999) did a research on the improvement of ECSS of vegetable crops. The major improvement was implemented by adding a regulated fan speed, water flow rate and wetted-thickness. This was conceivable as a result of varying temperature and relative humidity within the facility.

Dzivama, (2000) did a research on the execution evaluation of an active cooling system using the principles of ECSS of fruits and vegetables. He developed numerical models for the evaporative process at the pad-end and the storage chamber and a stem variety of sponge was considered to be the best pad material from the local materials tested as pad material.

2.4.2.1 Structural parameters of EC structure

Numerous researchers used different structural materials viz.; bricks, wood, mild steel, aluminum sheet as walls of the ECSS. Top of the ECSS was made of light weight, cheaper and easily available materials; asbestos sheet, gunny bag, jute bags, plywood, etc. (Chouksey, 1985; Roy and Khurdiya, 1986; Rama and Narasimham, 1991; Olosunde, 2009; Jha, 2008; Mishra *et al.*, 2009; Vala and Joshi, 2010; Samira *et al.*, 2011). These materials are less expensive and easily available. This makes construction cost of ECSS lower when compared with mechanical refrigeration.

Chinenye (2011) built an evaporative cooler with clay and other locally available materials. The performance of cooler was assessed in terms of temperature drop, evaporative effectiveness and cooling capacity. The outcome shows that the evaporative cooler can reduce the daily maximum ambient temperature from 32-40°C to 24-29°C i.e. a temperature reduction of up to 10°C and increase the relative humidity of incoming air from 40.3% to 92% for the storage structure. The saturation efficiency ranged from 20-

92% with a maximum cooling capacity of 1207 W. The evaporative cooler was able to preserve freshly harvested tomato for 19 days before obvious colour changes and mould spotting appeared and the weight drastically reduced.

Samira *et al.* (2011) had grown five hot pepper varieties at Haramaya University Research Farm, Ethiopia. Significant ($P \leq 0.05$) differences were observed among cultivars and storage conditions in changes in nature of pepper. The lowest and highest moisture contents were recorded in PBC 600 and Melka Eshet, respectively. The lowest weight loss and highest ascorbic acid content was recorded in Mareko Fana stored in evaporative cooler. After 16 days of storage, all pepper fruits stored at ambient condition were unmarketable while those kept in evaporative cooler were stored up to 28 days. The most elevated sharpness level was observed in ambient storage environment than in evaporative cooler. Evaporative cooling was shown to enhance shelf life by fourfold compared to the ambient condition. The shelf life of pepper was enhanced in all varieties tested while the quality attributes were maintained better in Mareko Fana than in the other varieties when harvested at mature green stage and stored under ECSS.

Gunhan *et al.* (2007) assessed the suitability of pumice stones, volcanic tuff and greenhouse shading net as alternative pad materials to the widely utilized and commercial one called CELdek. For this reason, the tests were carried out at four levels of air velocity (0.6, 1.0, 1.3 and 1.6 ms^{-1}) four levels of water flow rate (1.0, 1.25, 1.5 and 1.75 l min^{-1}) and three levels of pad thickness (50, 100 and 150 mm). The tests were made at $30 \pm 1^\circ\text{C}$ and $40 \pm 1\%$ relative humidity. During the tests temperature of water flow was kept constant at $25 \pm 1^\circ\text{C}$. As indicated by the results of this study, the volcanic tuff pads are good alternatives to the CELdek pads at 0.6 ms^{-1} air velocity.

Chouksey (1985) reported the configuration aspects of a solar cum- wind aspirator ventilated ECSS of 20-ton capacity for potatoes and other semi perishables, which was built at the Central Potato Research Station (CPRS), Jalandhar. The structure kept up a temperature of $21\text{--}25^\circ\text{C}$ with 80–90% RH at ventilation rate of $24 \text{ m}^3/\text{min}$ when the outside temperature and RH were $40\text{--}42^\circ\text{C}$ and 30–35%, respectively.

Jha (2008) built and tested a 5-tonne capacity ECSS at pilot scale for fruits and vegetables grown in hot and dry regions. Performance of ECSS was assessed in terms of temperature drop in ECSS and loss in weight of stored materials by preserving potatoes

(4.5 tonnes), Kinnow (4.5 tonnes) and tomatoes (0.5 tonne) during 2005 and 2006 at CIPHET, Ludhiana. Temperature drops at center of ECSS when compared with outside conditions were about 20°C (close to wet bulb depression of 23.5°C for prevailing outside conditions in corresponding day) and 17°C and rise in relative humidity from 10 to 65%.

2.4.2.2 Pad materials of EC structure

Pad is a vital part of ECSS. A pad material should be sufficiently porous to allow free flow of air. It should be able to absorb water and permit evaporation. It should have maximum amount of wetted surface area for an adequate period of air water contact time to accomplish near saturation. The material should be locally available and moderate. Moreover, it should permit easy construction into obliged shape and size (Liao *et al.*, 1998; Dzivama *et al.*, 1999).

Kouchakzadeh and Brati (2013) assessed the suitability of bulk charcoal as alternative evaporative cooling pad material utilized in greenhouses. A special test setup is intended to assess the performance of charcoal pad. The saturation efficiency and relative humidity difference were assessed. The outcomes show that the best average saturation efficiency in charcoal's bulk density 209.58 kg/m was 70%, with 1.38 m s⁻¹ air velocity and 0.19 kg s⁻¹ water flows for each square meter of pad.

Banyat and bunjerd (2013) studied the saturation efficiency of an evaporative cooler on different cooling pads. Two type of cooling pads made of a raw cotton fabric and a curtain fabric were comparatively studied. The impact of blower speeds at 725, 1015 and 1450 RPM and water flow rate of 26.9l.min⁻¹ were investigated. The outcomes showed that an average of the different temperature between inlet and outlet were 2.9°C and 1.7°C for a curtain fabric and a raw cotton fabric, respectively. Saturation efficiency of the cooling pads made of a curtain fabric was in the ranges of 46.3 to 61.3% and 29.7 to 39.2% for a raw cotton fabric.

Maurya *et al.* (2014) examined three types of cooling pad made of cellulose, aspen fiber, and coconut coir. This study was performed in summer and based on weather conditions of Bhopal, India; when maximum dry bulb temperature of air was 41.2°C and wet bulb temperature was 26.1°C. The relative humidity of 31.1% was calculated from online psychrometric calculator. Cooling efficiency of the cooling pads

made of cellulose was in the range of 64.55 to 55.29%, for aspen it was 80.99 to 68.86%, and for coconut coir 68.15 to 50.79% was observed. It is seen that the cooling capacity increases with air velocity and the cooling efficiency decreases with increase in velocity of air. It is also observed that the Aspen fiber has higher cooling efficiency while coconut coir has lower and the water consumption rate increases with air mass flow rate.

There is a great deal of exploration concentrating on the qualities and execution of different types of evaporative cooling pads, namely sand, clay, brick bats, date palm fibers and leaves, clay, wood saving, sack, saw dust, wheat straw, jute, PVC sponge, morum, pumice stone, coconut coir, rice husk, charcoal, cotton fabric, green house shedding net (Roy and Khurdiya, 1986; Abdalla *et al.*, 1995; Gunhan *et al.*, 2007; Jha, 2008; Tilahan, 2010; Vala and Joshi, 2010; Chinenye, 2011; Samira *et al.*, 2011; Banyat and Bunjerd , 2013) and man-made commercial cooling pads; aspen pad and rigid pad (CEL-dek) (Abdalla *et al.*, 1995; Al-Sulaiman, 2002; Vala and Joshi, 2010). Recently, new cellulose paper designs have been developed to make evaporative cooling more competent and more significant in diverse applications including modern and built-up sectors, greenhouses, beef, poultry, and swine buildings, as well as storage warehouses.

Performance of the pad material depends on outside weather, both temperature and humidity but the material having good porosity and air-water contact within the pad performed better when compared with others.

2.4.2.3 Operating parameters of EC structure

Cooling efficiency, temperature drop and increase in humidity inside the cool chamber relies great extent on working parameters. Optimum composed parameters for a given size gives better performance in terms of cooling efficiency. An active evaporative cooling system comprises of a pad (moist material), fan, storage cabin and water pump. Apart from the general requirements for the productive operation of an evaporative cooling system, the cooling efficiency of an active evaporative cooler depends on the rate and amount of evaporation of water from the pad. This is dependent upon the air velocity through the pad, pad thickness and the degree of saturation of the pad, which is a function of the water flow rate wetting the pad and the pad construction material (Dzivama, 2000).

Rayaguru *et al.* (2010) studied the Suitability ZECC for short term storage of fruits and vegetables was studied in coastal districts of Orissa. The optimum water level of 75 l/day and 90 l/day was required to accomplish a steady storage environment for storage of fruits and vegetables in summer and winter months, respectively. The chamber was kept temperature of its surrounding lower by 5–8°C than the outside temperature and maintained more than 90% RH. The ZECC was very effective in extending the shelf life of potato, tomato, brinjal, mango, banana and spinach by 3 to 15 days as compared to ambient conditions.

Improvement in saturation efficiency can be done with increase in pad density and pad thickness at certain level with proper water flow rate and pad-face velocity, than decreases for a particular pad material. Pad density, pad thickness, air flow rate and water flow rate are the important parameters considered for efficient design.

2.4.2.4 Performance of EC for different agro produces

EC storage structures were assessed for their usefulness in increased shelf-life of commodity, reduction in PLW, retention of nutritive value, curing effect, better ripening and other uses. The EC storage structure have been found suitable for increasing shelf-life of potato, grape, orange, banana, carrots, ber, pointed gourd, aonla, leafy vegetables, sapota, kinnow, bitter guard, capsicum, cauliflower, pineapple, peach and some other fruits and vegetables (Roy and Pal, 1991; Singh and Satapathy, 2006; Jha, 2008). The EC storage structure can be utilized for short-term storage of perishable commodities, when outside atmosphere is hot and dry. Evaporative cooling system should be suggested for use by small scale farmers, retailers, wholesalers and exporters to nearby neighboring nations.

Murugan *et al.* (2011) studied the efficiency of earthen pot cool chamber (EPCC) to store vegetables and fruits such as tomato, grapes and brinjal. The quality retaining capacity in the products kept in earthen pot cool chamber was compared with other type of storage system like refrigeration and room temperature. After 9 days of storage, PLW, changes in microbial nutrient and organoleptic properties were evaluated. The products stored in earthen pot cool chamber were fresh and less affected when compared with other storage system. The study revealed that the EPCC is a good storage system to keep the vegetables in fresh condition.

Looking to the advantages and suitability of ECSS in country, this can be constructed in numerous parts for storage of fruits and vegetables at low cost as compared to costly mechanical refrigeration system. Being simple in design and operation, this system will be useful in reducing the post-harvest losses at farm level.

2.5 Sources of Energy for Cooling Technology

Globally 15% of the electrical energy from the grid is utilized for refrigeration in areas where power is available (James and James, 2011). Other than these energy sources there is an option of energy provision from natural energy sources that include among others solar and wind energy. Systems based on fossil fuels are being discouraged as they contribute two-thirds of greenhouse gas outflows (Best *et al.*, 2012). The impact of fossil fuels in escalating the problem of global warming led to the technological shift towards the use of clean energy that includes solar, wind energy and other renewable energy sources for refrigeration of fruits and vegetables. Solar energy can be converted to heat or to electricity so as to power a compressor and fan in mechanical refrigeration systems (Fan *et al.*, 2007).

2.5.1 Solar energy option

Solar energy is a viable alternative to fossil fuels as it is clean and uses the natural energy from the sun to generate electric power. Barbosa (2007) perceives the need to introduce energy supply especially, to rural population and this would apply to small scale farmers, for increased productivity and for income generation. As per Best *et al.* (2012), the utilization of solar energy for refrigeration purposes in the Agro-industry has a potential in developing countries. This is more so as the solar energy is accessible throughout the year with values in excess of 2000 kWh/m. There is a potential energy saving of 40-50% when solar driven air conditioning systems are utilized versus conventional systems.

Feasibility studies of this technology have been carried out in Mexico and the Mediterranean area (Ayadi *et al.*, 2008) and these have showed that it is conceivable to obtain temperatures as low as -2°C for air-cooled systems utilizing solar energy as a source. There are mainly two types of technologies for solar refrigeration i.e. solar electric and solar thermal (Kim and Ferreira, 2008). In the solar electric system solar

energy is converted to electricity by utilization of photovoltaic (PV) cells that operate a vapour-compression refrigeration technology, while with solar thermal systems solar energy heats the working fluid in the generator of vapour sorption to generate refrigeration impact. Thus, there have been reasons for focusing on the potential of converting solar energy through PV systems for utilization in agriculture as a basis for sustainable agricultural production (Ekren *et al.*, 2011).

With the intensification use of PV systems in numerous remote areas the international costs have fallen sharply from US\$10 in the 1980s to US\$3 per Wp. There are energy requirements for agriculture in rural areas for agro-processing and irrigation purposes which must be met by alternative sources of energy other than grid electricity. The grid electrification is costly and yet all energy requirements can be met by other sources of energy including solar energy through use of PV systems. As indicated by Cugala *et al.* (2009), rural electrification programmed will not reach all the rural population and therefore, there is a need to find other intends to supply confined limited needs. This is especially so “for remote, scattered populations with low and scattered energy demands”. These needs could then possibly be reached by PV systems though it is acknowledged that this system requires specialized training and back up and maintenance services. Use of PV systems found use in pumping systems for drinking water and these have been set up in numerous nations as they have proven to be technically feasible and economically competitive.

2.5.2 Solar energy and its characteristics

The Earth receives 174 petawatts (PW) of power of incoming insolation at the upper atmosphere. Approximately 30% is reflected back to space while the rest is absorbed by oceans, clouds and land masses. The spectrum of solar light at the Earth's surface is mostly spread over the visible and near-infrared ranges with a little part in the near-ultraviolet.

The total solar energy absorbed by earth's atmosphere, land masses and oceans is approximately 3,850,000 exajoules (EJ) per year. In 2002, this was more energy in one hour than the world used as a part in one year. Photosynthesis catches approximately 3,000 EJ per year in biomass. The technical potential accessibility from biomass is from 100 - 300 EJ/year. The amount of solar energy reaching the planet surface is so vast that

in one year it is about twice as much as will ever be obtained from all of the earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined. Solar energy can be harnessed at different levels around the world, mostly relying upon distance from the equator.

2.5.3 Solar operated instrument, device and machines

Ma (1993) patented a solar power operated computer comprised of an upper casing and a base pivoted together, the upper casing and the base each having a solar cell assembly respectively hinged thereto to collect the radiant energy of sunlight and convert it into electric power for charging respective storage batteries. The upper casing with its solar cell assembly may be detached from the base for independent use as a touch-control type or pen base computer.

Pande *et al.*, (2003) planned and developed solar PV pump based drip system for orchards. The solar PV system comprising of a PV pump with 900 watt PV array and 800 watt of DC motor pump mono block with micro filters. The system could be able to irrigate 1 ha area within 2 hours with discharge of 3.8 l/h in the pressure 70-100 kPa.

Pande (2009) developed and assessed Solar PV winnower cum dryer. It can be utilized throughout the year for one or other purposes. The system throughput capacity was found to be 200-300 kg per day with 6 daylight hours. The system was found effective as a sub system of solar dryer. Dryer utilizing the winnower's fan, the nature of the dehydrated product was observed higher than conventional sun drying. The solar winnower assisted dryer was found efficient in reducing time of drying from 50-70 h to 24-28 h only with uniform drying.

Moreno-Quintanar *et al.*, (2011) worked on a solar intermittent refrigeration system for ice production. The system was intended to produce up to 8 kg/day of ice. The system consists of a compound parabolic concentrator with a tube type receiver acting as the generator/absorber, a condenser, an evaporator and an expansion valve.

Wang *et al.* (2012) worked on solar-assisted cascade refrigeration system. The system consists of electrical power operated vapor compression refrigeration system and solar-driven vapor absorption refrigeration system. It was connected in series with vapor absorption refrigeration system. Refrigerant and solution reservoirs are intended to store potential to keep the system operating continuously in absence of solar energy. As per

results the system obtains pretty higher COP as compared with the conventional vapor compression refrigeration system. COP of the new-type vapor compression refrigeration system increased when sunlight becomes intense.

From the above review, it is evident that a substantial work has been done on extending the shelf life of fruits and vegetables by modification of the storage environment by the application of evaporative cooling. Some of storage structures are passive type and some operated with the grid power. The use of solar energy for cooling system in all the cases that have been discussed has been limited to buildings. There seems to be success story of using solar energy to power evaporative cooled storage structure and this provides an opportunity to preserve or to be extended the shelf life of fresh produce. The use of solar energy to power a water pump and fan is very limited that can be utilized for active evaporative cooling of fruit and vegetables.

This chapter distinguishes the materials used and methods followed in conducting the experiment on solar powered evaporative cooled rural storage structure (ECSS) for fruits and vegetables. The study was conducted to assess the effects of pad materials and pad area on environmental parameters inside the structure and to evaluate of quality of stored produce in the developed storage structure.

3.1 The study was planned in the following sequence:

- i. Conceptual design of solar powered ECSS for fruits and vegetables
- ii. Selection of suitable low cost materials and fabrication of storage structure (1 m³ capacity)
- iii. Testing of structure under no-load condition
- iv. Evaluation of the effects of pad materials & pad area on environmental parameters inside the structure
- v. Testing of structure under load condition
- vi. Evaluation of quality of stored produce in the developed storage structure
- vii. Statistical analysis of experiment data

3.2 Design process

A theoretical design of the ECSS was done considering the following parameters

- a) Storage chamber
- b) Water circulation system
- c) Air circulation

The theoretical configuration was translated to the actual design used for the development of the ECSS.

3.3 Design Consideration

The design considerations constitutes following points

- Design of evaporative cooler with locally available affordable material

- A square or near to square room most economical and efficient as in that surface areas per total volume minimized the construction costs and reduce heat losses

3.3.1 Theoretical design

The following factors were determined

- The storage capacity limit of the chamber depends on farmers' requirement. The cooling load incorporate the calculation of fresh produce field heat at harvest and the respiratory heat production used to outline cooling load.
- The ventilation rate (m^3/s) serves to determine and to choose the right fan size. The cooling pad size influences the measure of water flow per unit time. The amount of water flow per unit time will help determine the pump size.

3.4 Design of storage structure

Based on the theoretical design, an ECSS was built that will accommodate a maximum of 1 m^3 of storage capacity of chosen fresh produce.

3.4.1 Height of structure

For convenience in operation, loading and unloading of the produce and the other maintenance practices at the field, the structure height should not exceed 2 m. Similarly, to accommodate the common fruits and vegetables crates available in the market with reasonable air gap both at sides and bottom, it was decided that the structure height should be kept at a minimum of 0.5 m. So the height of storage structure was selected as 1.6 m so that it should be easy to enter and work. It also makes structure walk in type.

3.4.2 Floor of structure

The floor of the storage cabin was made 20 cm above the floor. The 20 cm gap between the ground and the storage cabin helps to reduce the losses of heat of structure directly through conduction to the ground. It also protects the structure from corrosion due to water accumulated on the ground during rainy season. It is made of 18 gauge MS sheet and supported by 1 inch angle iron. The ms sheet floor of storage cabin makes the bottom of the structure close to reduce the threat of rodents' entry.

3.4.3 Shape of structure

For handling fruits and vegetables containers generally used in the market (mandis) are of box type. Hence, the overall configuration of the structure was decided to be of parallelepiped or rectangular box type, so that the inner space could be efficiently utilized. Besides, the construction of a structure with rectangular cross section is much easier than that with any other cross section.

3.4.4 Storage Cabin

Design capacity of storage structure = 1 m^3

Containers which do not restrict flow of air through them like the commonly available plastic crates were used to store the fruits and vegetables.

$$\begin{aligned}\text{Volume of a crate} &= L \times B \times H \quad \dots (3.1) \\ &= 56.5 \times 36.5 \times 27 \text{ cm} = 55680.75 \text{ cm}^3 \\ &= 0.05568 \text{ m}^3\end{aligned}$$

Taking 10% volume as free board, actual useful volume = 0.050112 m^3

$$\begin{aligned}\text{No. of crates in } 1 \text{ m}^3 &= \frac{1}{0.050112} \\ &\approx 20 \text{ crates}\end{aligned}$$

Let there be 1 crate in length and 2 crates in width in a stack.

$$\text{No of crates/layer} = 2$$

If there are 5 layers in a stack, total no. of crates/stack

$$= 2 \times 5 = 10$$

Hence the number of stacks required = $\frac{20}{2} = 2$

To avoid direct contact of the crates to the evaporative cooling pad with the side walls of ECSS, some gap has been maintained between the crates and structure walls.

The clear distance between the walls and the crates = 0.1 m

Alley width (distance between the crates) = 0.8 m

$$\begin{aligned}\text{Width of the floor} &= (2 \times 0.1) + (2 \times 0.6) + (0.1) \\ &= 1.5 \text{ m}\end{aligned}$$

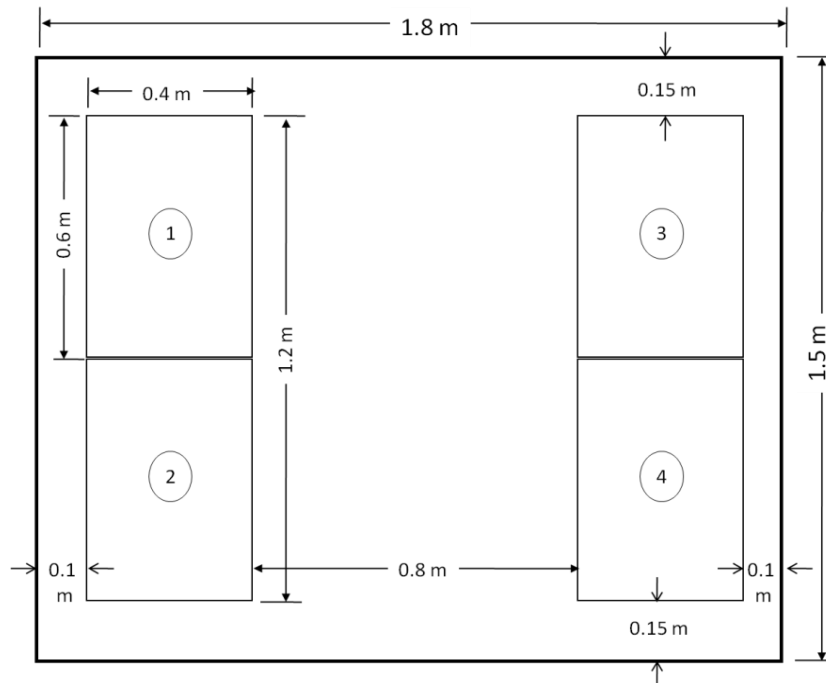


Fig.3.1. Floor diagram of ECSS

So the overall dimension of storage cabin was taken as 1.8 x 1.5 m. The height of storage cabin was kept as 1.6 m above the floor. The shape of the cooler is cuboids. The main frame of storage structure was constructed with 1.5 inch angle iron. The four angle iron rod of 1.8m are placed vertically and other eight angle iron rod (four of 1.8m and four of 1.5m length) were welded horizontally such that a frame is formed. 1 inch flat plate and 1 inch angle iron were welded in frame to hold the pad with pad holder in frame. The portable top cover of the storage cabin has been made as a truncated pyramid type shape (frustum) of 16 gauge MS sheet simply supported over the cabin wall at its circumference and also by 1 inch angle iron rod. The central square opening is provided for fan fitting and covered with the pot toppers to protect the fan from rain. The evaporative cooler has a 4-way entrance and one way air exit form top. 4 sets of cooling pads are installed in each entrance. It was not necessary to fabricate the whole structure

on site. Rather, different components of the structure were prefabricated in the Workshop of Division of Agricultural Engineering, IARI, which were assembled on the experimental site

Total volume of the structure (V) = Volume of cube (V₁) + Volume of frustum (V₂)

$$\begin{aligned}\text{Volume of cube (V}_1\text{)} &= 1.5 \times 1.8 \times 1.6 \text{ m} \\ &= 4.32 \text{ m}^3\end{aligned}$$

$$\text{Volume of frustum (V}_2\text{)} = \frac{h}{3} (A_1 + A_2 + \sqrt{A_1 A_2}) \quad \dots (3.2)$$

$$A_1 = 0.25 \times 0.25 \text{ m} = 0.0625 \text{ m}^2$$

$$A_2 = 1.5 \times 1.8 \text{ m} = 2.7 \text{ m}^2$$

$$V_2 = \frac{0.3}{3} (0.0625 + 2.7 + \sqrt{0.0625 \times 2.7})$$

$$V_2 = 0.3173 \text{ m}^3$$

$$\text{Total volume (V)} = 4.32 + 0.3173$$

$$V = 4.6373 \text{ m}^3$$

3.5 Heat load on storage structure

The cooling load of a system required for a particular application is determined by several factors. The heat load is calculated for storing ripe tomato 1 m³ (500 kg) in the storage structure (Sahay and Singh, 2001).

3.5.1 Conductive heat gain

It is heat gained/lost through the building floor, walls and ceiling by conduction. Conduction gain/loss is dependent upon the Temperature differences between the inside and Outside of the cold room and insulating value of the Floor, walls and ceiling.

The steady state heat flow (W) by conduction is given by following equation.

$$Q = U A (T_o - T_i) \quad \dots (3.3)$$

The overall heat transfer is given by

$$\frac{1}{U} = \frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \dots + \frac{1}{h_i} = \frac{1}{h_o} + \sum_1^n \frac{x}{K} + \frac{1}{h_i} \quad \dots (3.4)$$

Where, A = area through which heat is transferred

U = overall heat transfer coefficient

A = area through which heat is transferred

T_o & T_i = temperature of outside (308 K) & inside (298 K) air respectively

h_o & h_i = heat transfer coefficient on outer and inner surface respectively
= 5 & 1.9 W/m².K when fluid is air and transmission surface is mild steel & cellulose pad respectively

$\sum_1^n \frac{x}{K}$ = thermal resistance of the materials used for the construction of the wall

Table 3.1 Conductive heat gain of ECSS

Conductive heat		Area, m ²	Thickness, mm	U value, W.m ² K	Q, kJ/day
Walls	Mild steel (k ₁)	0.9	1.214	2.50	1943
	Pad (k ₂)	9	50	0.774	6025
Floor (k ₁)		2.70	1.214	2.50	5832
Ceiling [MS* & asbestos sheet ⁺ (k ₃)]		2.75	1.214* & 6 ⁺	2.28	5430
Q = 19230 kJ/day					

Where, k₁, k₂ & k₃ = 54, 0.21 & 0.16 J/s m K respectively

3.5.2 Chilling load

$$Q_c = m c_{pm} (T_1 - T_2) \quad \dots (3.5)$$

Where, m = mass of the product = 500 kg

c_{pm} = mean specific heat of product = 3.977 kJ/kg.K

T₁ - T₂ = difference between initial and final temperature of the product
= 308 K - 298 K = 10 K (assumed)

$$Q_c = 500 \times 3.977 \times 10 = 19885 \text{ kJ}$$

The heat generated by the food material/day

$$Q_g = m h_g \quad \dots (3.6)$$

$$= 500 \times 3.5 = 1750 \text{ kJ/day}$$

Where, h_g = heat generated per kg of product per hour = 3.5 kJ/kg.day

3.5.3 Convective heat gain

It is heat that is transferred by Convection, the mixing of outside air with the cold inside air. The smaller the room, the more of the Relative volume of air is exchanged during each Opening and closing of the structure.

Heat load due to air infiltration

$$Q_a = 4100 \text{ kJ/day}$$

3.5.4 Equipment heat load

It is the energy gained from Equipment operating in the room. This includes fan Motors, light fixtures, defrost equipment, as well as Forklift motors (4484 kJ/HP for motors under ½ hp).

$$Q_e = \frac{kW}{\eta} \times \text{load factor} \times 3600 \times 24, \text{kJ/day} \quad \dots (3.7)$$

Where, η = efficiency of motor = 60%

$$Q_e = \frac{0.048}{0.60} \times 1 \times 3600 \times 24 = 6912 \text{ kJ/day}$$

3.5.5 Human energy load

It is the amount of energy Expended by the number of workers in the room for Certain time periods within a 24-hour period (Average of 712 kJ/worker-hour).

One man worked for ½ hour in a day, then

$$Q_h = \frac{1}{2} \times 712 = 356 \text{ kJ}$$

$$Q_{\text{total}} = Q + Q_c + Q_g + Q_a + Q_e + Q_h$$

$$= 19230 + 19885 + 1750 + 4100 + 6912 + 356$$

$$= 52233 \text{ kJ/day} = 604.5 \text{ W} \quad (1 \text{ J/s} = 1 \text{ W})$$

$$\text{Ton of refrigeration (TOR)} = \frac{52233}{336000} \quad (\text{one TOR} = 336,000 \text{ kJ/day})$$

$$= 0.155$$

0.155 tonnes of refrigeration or 604.5 W is the required ECSS cooling capacity.

3.6 Water Distribution Network

Probably the most important aspect of an evaporative air cooling is its water management system. The water distribution network consists of pipe network, a distribution and collection tank and a bottom channel to take the excess water to the tank.

3.6.1 Water Flow Rate

Evaporative cooler manufacturers recommend water flow rates to the evaporative cooling pad ranging from 4-6 l/min for each meter length of the distribution pad for coolers up to 1.8 m high. A flow rate of 5 l/min/m of distribution pad surface area for evaporative coolers up to 1.8 m high have been shown to work satisfactorily. A valve should be placed in the line from the pump so the water flow through the distribution pipe can be adjusted.

The water distribution system was fitted on the top of this frame and the water was distributed over the upper face of the evaporative pad by a tube, with many holes to drip the water evenly onto the pad face. The pipe was made of PVC, 25 mm in diameter and had 2 mm diameter holes drilled on 50 mm distance along the top of the distribution pipe. Pad was continuously kept wetted.

Water contains a certain amount of un-dissolved minerals and usually carries pollutants and other fine particles such as pollens. When evaporation takes place that will increase mineral and other particle concentration in the remaining water. To avoid build-up, this water is dumped or discharged periodically.

3.7 Selection of electrical accessories based on design requirement

3.7.1 Recirculation pump

Water flow rate	=	5 l/min per meter length
So the water flow rate through the single pad	=	5 x 1.5
	=	7.5 l/min
Total water flow rate	=	7.5 x 4
	=	30 l/min

As per the need, considering the frictional losses a 40 l/min underwater cooler pump is used for recirculation of water through the pad. The water is being pumped by the pump to the height of 2.5 m by the cooler's pipe. The recirculation pumps are vital to keeping pads fully wetted during operation.

During the month of summer pumps and sumps should be cleaned several times of operation to prevent sludge and algae or sediment clogging that reduced water pressure across the distribution header and non-uniform, poor pad wetting. Extreme clogging may cause the entire system to fail and water recirculation pumps to burn out. Sump pump water level is also checked and adjusted if required to make sure enough water is available for cooling.

3.7.2 Water storage and collection

The water collected by the bottom gutter is returned to a sump from which the water is pumped to the upper distribution pipe or gutter. The gutter is made of 18 gauge GI sheet with the dimension of 10 x 10 cm all along the length of bottom of pad. The sump should have a minimum capacity of 30 l for each square meter area of the distribution pad for coolers in order to hold the water that drains back to the sump when the system stops.

An evaporative cooling system needs to have sufficient water storage to keep the pads fully wetted when system is running. To save water and pumping costs, make sure system is not losing water through leaks and gaps in the plumbing/troughs. Cracked troughs must be checked.

$$\text{The total pad area} = 9 \text{ m}^2$$

$$\begin{aligned}\text{Minimum sump capacity} &= 9 \times 30 \\ &= 270 \text{ l}\end{aligned}$$

As per the availability a plastic water tank of 500 l was used as the sump tank. The water tank was periodically filled.

3.7.3 Exhaust fan

A negative pressure is needed to be created inside the structure which is a function of the pad and the fan, when this happens, air at a positive pressure rushes into

the system through the pad. For proper air circulation, and the best desired airflow pattern, the fan was located at the central position at the top which now allows air to be drawn from the pad area which in turn draws the cool air and expel the humidified air out. Evaporative air cooling use very little energy, but most of used for the fan.

The axial- flow exhaust fan was fixed at the top of ECSS to control the relative humidity and reduce concentration of carbon dioxide released by stored produce inside the storage structure. Fan is selected as made of Sturdy metal body with metal blades and metal bird screen for protection from birds & foreign matter. The fan has 3 blades with sweep diameter 225 mm the other specification of fans are 230 V, 48 Watt 50 Hz 1 phase AC and 1300 rpm.

3.7.4 Thermostat

Thermostat is used as the instrument for automatic temperature control. In temperature control in fruits and vegetables store, the thermostat is always a part of a circuit, which activates the electric control switch. The thermostat performs the following function together with the temperature sensor: temperature sensing temperature measurement, comparison of measured and set temperature and decision as to whether or not the control switches are to be actuated.

3.7.5 Electrical load estimation

The load consists of a fan (48 W) and a water pump (40 W). The PV system consists of 4 PV solar panels, one inverter (1250 VA), one charge controller and a battery bank. Each PV panel generates 100 W_p. For an AC system requires an inverter, an electronic component that converts DC electricity from the solar panels into AC electricity to operate the fan and pump.

The electric current produced by SPV panels during daylight hours charges the batteries, and the batteries in turn supply power to the system. For maximum utilization of solar energy solar modules are moving type and carefully oriented so they face true south (not magnetic south). The use of batteries with inverter gives electricity for a longer period of time by providing a consistent operating voltage to the water pump and fan. Thus, during the low light periods and night, the system can still provide a constant power.

$$\text{Fan 48 W for 24 hours} = 1152 \text{ W}$$

$$\text{Water pump for 24 hours} = 960 \text{ W}$$

$$\text{Total power usage daily} = 2112 \text{ W}$$

So the daily power requirement said to be 2.112 kWh

Divide the total daily power requirement by the number of charge hours (sunshine taken as 6 hours)

$$= \frac{2112}{6} = 352 \text{ W}$$

$$\text{Adding 10 \% for inefficiency} = 387.2 \text{ W}$$

This total power value determines the size and number of panels (each panel 100 W)

$$= \frac{387.2}{100} = 3.872 \approx 4 \text{ panels}$$

Each of two panels are connected in series (resulting in doubling of voltage) and then connected in parallel to the two pairs previously connected in series (so as to have doubled current).

$$\text{Total Battery capacity} = \frac{2112}{24} = 88 \text{ AH}$$

$$\text{No. of 75 AH Battery} = \frac{176}{75} = 1.17 = 2 \text{ Batteries}$$

(Batteries of 12 V each connected in series)

The system was turned on at 10:00 am and turned off at 4:00 PM. When the inside temperature dropped to $\leq 25^{\circ}\text{C}$ the system was turned off. When the temperature reached $> 25^{\circ}\text{C}$ the system was turned on. This process was carried out by means of thermostat.

3.7.6 Electrical wiring

Electrical wiring and connection should be electrically and mechanically secured. The cable passes through the metal edges, metal holes, attached with agromet of suitable insulating material, so as to the protect cable from harm and possible earthing.

The metal casing of the electrical parts, metal casing or casing of cooler cabinet and all uncovered metallic parts, prone to become live, provided with earthing facilities. Provision be made to run fan and pump set separately and a thermostat is connected in

between switches of fan-motor connection. The three-core-cable with appropriate length provided with each component.

3.8 Pad material selection

The selection on the type of pad used in the design was based on the following conditions:

- Porosity
- Water absorption/ evaporation rate of the material
- Availability
- Cost
- Ease of construction

Based on the following above mentioned requirements the three local available materials are tested as cooling pad:

- CELdek pad (50 mm thickness)
- Wood wool pad (50 mm thickness)
- Khas khas (Vetiveria Zizanoides) mat (50 mm thickness)

3.8.1 Pad-holders

Pad-holders were constructed for the coolers so that they were not limited to cloth-like pads that would only wrap round the cooler. The pad-holders therefore make the coolers more versatile, effective and easy to change the pad. The pad is held in place by 1 inch angle iron and 1 inch MS flat frame work and 10 gauge wire mesh which supports it from one side. A rectangular large hole which allows air movement into the pad constitutes the cross-section of the wire mesh. The size of the holes of the wire mesh was 35 mm by 35 mm. Small GI wire pieces are used to hold the pad together with the pad holder to prevent sagging of the pad. Each pad material (wood wool and khas khas mat) are attached to the pad holders with the help of GI wire each of 4 set.

$$\begin{aligned}\text{Area of a pad} &= 1.5 \times 1.5 \text{ m} \\ &= 2.25 \text{ m}^2\end{aligned}$$

$$\text{Total no. of pads} = 4$$

$$\begin{aligned}\text{So, the total pad area} &= 4 \times 2.25 \text{ m}^2 \\ &= 9 \text{ m}^2\end{aligned}$$

Four vertical pads each of material (wood wool and khas khas), 1.5 x 1.5 m were fabricated manually by filling the pad material in a wire net at a specific pad thickness to provide a constant pad density.

CELdek pad is available in the size of 1.5 x 0.6 x .05 (h x b x t) m and 1.5 x 0.3 x .05 m. for each side set of 1.5 m length was used.

3.8.2 Cooling Pad Area

We must have adequate pad surface area to maximize operating efficiency, and an adequate water supply and distribution system. The pad area needed depends upon several factors including the type of pad material used. The pad should be continuous along the entire length of the wall. The evaporating surface area is also an important factor that affects the rate of evaporation. The greater the surface area from which the water evaporates, the greater the rate of evaporation.

To find out the significance of optimum pad area four different pad areas are used. So the system cooling efficiency for each of the material with different surface area is determined.

Single side pad wall	:	2.25 m ²	(1 x 1.5m x 1.5m)
Double side pad wall	:	4.5 m ²	(2 x 1.5m x 1.5m)
Three side pad wall	:	6.75 m ²	(3 x 1.5m x 1.5m)
Four side pad wall	:	9 m ²	(4 x 1.5m x 1.5m)

For using the pad on specific side the other sides are covered with the 150µm greenhouse polythene so that air could not enter through that side.

3.9 Optimization of selected variables for developed ECSS

No-load test of the evaporative cooling system

- Temperature and relative humidity measurement

Load test of the evaporative cooling system

- Temperature and relative humidity measurement
- Physiological weight loss
- Firmness

3.9.1 Experimental site

The experiments were carried out in the premises of Energy lab, Division of Agricultural engineering, ICAR-Indian Agricultural Research Institute, New Delhi during 2014-15, which lies at latitude 28.63°N and longitude 77.2°E.

3.9.2 No-load test of the evaporating cooling system

A no-load test was conducted on the system to see the effect of the evaporation that is expected to take place whether the process is effective or not and to determine its efficiency with different independent variables before being loaded with the horticultural produce that will be stored. This is computed by measuring the relative humidity and temperature difference. The efficiency of the system is measured under three different material and four different pad area.

3.9.2.1 Measurement of different parameters

For the validation of solar powered ECSS for fruits and vegetables the following parameters were measured during the experiments.

3.9.2.2 Insolation

Insolation (W/m^2) was measured at 2 hour interval with a thermoelectric pyranometer, which was set in the same plane as the panels for instantaneous insolation measurements on panel surface (at tilt) and on horizontal surface, and the reading was taken with the help of Solar Power Meter (KM-SPM-11).

3.9.2.3 Voltage and current

For testing the performance of Solar PV system the current (I_{SC}), Amps and voltage (V_L) is measured for battery and inverter each by the multimeter (FLUKE 73 series multimeter) that used to calculate the power output of Solar PV system.

$$\text{Power (W)} = V \times I \quad \dots (3.8)$$

3.9.2.4 Temperature & Relative humidity

The difference between the external and internal temperatures will determine whether evaporation is efficient for the system. The temperature readings were taken using temperature sensors. Evaporative cooling performance is dynamic due to continue change in external temperature and humidity level.

Relative humidity is the measurement of the amount of water vapour in the air as a percentage of the maximum quantity that the air is capable of holding at a specific temperature. The temperature and relative humidity reading were taken at 10 am, 1 pm and 4 pm with three replications each of the time.

3.9.2.4.1 Temperature & Relative humidity Outside ECSS

The ambient temperature (T_o) was measured under shade to avoid the effect of direct solar radiation by using Hygro-Thermometer “Combination of digital Thermometer- Hygrometer with Max/ Min-memory” (Temperature range 263.16 to 333.16 K and humidity range of 10-99%). The ambient relative humidity RH_o was measured under shade to avoid the effect of direct solar radiation with the help of same instrument used for measuring ambient temperature.

3.9.2.4.2 Temperature & Relative humidity Inside ECSS

Inside ECSS the temperature and relative humidity were measured at the center of the structure with the help of a data logger with operating temperature between -40°C to 60°C (Model No. VA120900345) and operated with battery (Lithium 3.6V 1200mAh)

The psychrometric relationship was used to determine the wet bulb temperature values with the help of measured dry bulb temperature and relative humidity values.

3.9.2.5 Cooling Efficiency

The degree to which the leaving air dry bulb temperature approaches the wet bulb temperature of entering air is expressed as cooling efficiency. It is expressed as:

$$\text{Cooling efficiency} = \frac{T_{db} - T_{db}'}{T_{db} - T_{wb}} \quad \dots (3.9)$$

Where,

$$\begin{aligned} T_{db} &= \text{dry bulb temperature of inlet air.} \\ T_{db}' &= \text{dry bulb temperature of outlet air.} \\ T_{wb} &= \text{wet bulb temperature of inlet air.} \end{aligned}$$

3.9.3 Load test of the Evaporative cooling System

The pad material having the highest cooling efficiency in No-load test was used for testing of the evaporative cooler under load condition. The quality assessment of the

produce was estimated and the fruits and vegetables selection was based on the low shelf life.

3.9.3.1 Fruit Preparation and Storage

Fresh fruit & vegetables were purchased in the morning from the local wholesale market. Depending upon the nature of the fruit & vegetables, these were prepared for storage. Spinach, tomato, capsicum, cucumber(with trimmed taproot and stem plates), bottle gourd, green beans, pointed gourd (*Trichosanthes dioica*), Papaya (fruit) were washed with bore water for cleaning dust and impurities attached to vegetables and also to bring down its temperature.

3.9.3.2 Weighing of tested samples

The weights of tested samples for different measurements were determined with the help of an Electronic balance (Resolution of 0.1g and Max 1 kg) and an ordinary electrical balance (Resolution of 1 g and Max 15kg).

5 kg fruit and vegetables were kept in plastic crates and stored in ECSS while the each of 10 samples more than 100 gm were packed in sterile poly meshes net bags. The initial weight of the sample is noted and stored in ECSS storage structure (5 samples) and in room (5 samples at room temperature).

3.9.3.3 Physiological Loss of Weight (PLW)

Most fresh horticultural produce contains from 65 to 95% water when harvested. Water is an important constituent of most of the fruits and vegetables and it adds up the total weight. Losses of water will reduce the weight of produce. When the collected produce loses 5 or 10% of its fresh weight, it starts to wilt and soon gets unusable. The loss of weight comprises of both evaporative and respiratory losses. The former, which happens as a result of respiration, depends mainly on the temperature of the surrounding air (FAO, 1989).

The weight of the produce after few days were estimated and compared with their initial weight. The difference in the weight was estimated by storing the produce both in the storage structure and in the room (ambient condition). This was done for some period of time to discover the effect of storing the two produce both in the ambient and in the ECSS.

$$PLW = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100 \% \quad \dots (3.10)$$

3.9.3.4 Fruit firmness

Ripening of fruits and vegetables has a direct connection with the firmness and since respiration and chemical activity continues even after harvest the fruits have the tendency become over-ripe and delicate. When fruits and vegetables are stored at low temperature and high relative humidity it slow down the metabolic activities viz., rate of respiration thus automatically slow down the changes in firmness.

Firmness of fruits and vegetables can be measured by puncture or compression each sample thrice at equal distance of 10 mm on equatorial region using texture analyzer (TA-Hdi, Stable Micro systems, UK) equipped with 50 kg load cell and stainless steel probe of 2 mm diameter. The operating parameters of texture analyzer were pre-test speed, 5 mms⁻¹, test speed, 1 mms⁻¹ and post-test speed, 5 mms⁻¹. Firmness was measured as the maximum force recorded in a force–time curve obtained from a Texture Analyzer during the compression of fruits and vegetables by the cylinder probe. The firmness of fruits and vegetables was measured in three places of each sample and average values were recorded for the study.

3.9.3.5 Colour Changes

Fruits ripening process continues even after harvesting which could be an important factor to be noted during post-harvest operations. The change in the colour of the produce was also noted both in the cooler and in the ambient condition. The colour changes were based basically on the physical appearance of the fruits and vegetables.

The colour of Fruits and vegetables in terms of L, a, b values were determined using HunterLab miniScan XE Plus colourimeter (HAL, USA, Model 45/0-L). The instrument was standardized with a white plate standard (Standard No. LX17760; X = 79.31, Y = 84.11 and Z = 88.94). L denotes the darkness or lightness, a, green or red and b, blue or yellow colour of the produce. The nose cone was positioned in the surface of the fruits and vegetables such that the light thrown by the colourimeter is not leaked. The colour was measured in three places of each sample and average values were recorded for the study. Before measuring, the colourimeter was standardized with white and black calibration tiles provided with the instrument.

3.9.4 Shelf life in days

The shelf life of fruits and vegetables was determined by subjectively judging the criteria of unmarketability parameter such as changes in colour and softening of the fruits mainly attributable to physiological loss in weight. The shelf life of the fruits and vegetables were calculated mainly on the basis of change in physiological weight (if more than 10% shelf life completed).

3.10 Statistical analysis of variables

The experiment data were analyzed using randomized complete block design (RCBD). The factors considered and the levels of variables are furnished in table 3.10.

3.10.1 Selection of suitable material for ECSS

The statistical package SAS was used to analyze the experimental data. This was done to obtain the necessary analysis of variance of the mean and interaction of the selected variables viz., different types of pad material and pad area as well as the dependent variables viz., cooling efficiency (%) for the different type of pad material and pad area under no-load condition.

Table 3.2 Design layout of RCBD experiment to assess the cooling efficiency for selection of suitable material

Sr. No	Variables	Levels
Independent variables		
1.	Pad material	X ₁
2.	Pad area	X ₂
Affected response variables		
1.	Cooling efficiency	Y

The following relationship was used for analysis.

$$Y = f(X_1, X_2)$$

3.10.2 Performance evaluation of ECSS

The statistical package SAS was used to analyze the experimental data. This was done to obtain the necessary analysis of variance of the mean and interaction of the selected variables viz., storage in evaporative cooled storage structure (ECSS) and in room condition as well as the dependent variables viz., PLW (%) and firmness (N) of fruits and vegetables.

Table 3.3 Design layout of RCBD experiment to assess the performance of ECSS

Sr. No	Variables	Levels
Independent variables		
1.	ECSS stored	X_1
2.	Room storage	X_2
Affected response variables		
1.	PLW	Y_1
2.	Firmness	Y_2

The following relationship was used for analysis.

$$Y_1 = f(X_1, X_2)$$

$$Y_2 = f(X_1, X_2)$$

The research work was conducted to evaluate the performance of three types of evaporative cooling pads [CELdek pads, wood wool pads and khas pads] and four different pad area [2.25m^2 (pad at one side), 4.5m^2 (pad at two sides), 6.75m^2 (pad at three sides) and 9m^2 (pad at four sides)] for the cooling in evaporative cooled storage structure. Their performance was evaluated based on difference in temperature, relative humidity and cooling efficiency.

Different fruits and vegetables were used to evaluate the effectiveness of the ECSS under load condition. The parameter for the shelf life evaluation included the percentage physiological loss in weight (PLW %) along with the change in colour and firmness. The findings of the present study have been presented in this chapter.

4.1 Performance of solar photovoltaic system

Average solar intensity was measured at surface of solar PV panel (Tilt surface) and at horizontal surface at 10:00 am, 12:00 pm, 2:00 pm and 4:00 pm during the preliminary experiments of 12 days (Fig.4.1). The maximum solar intensity was found as 1070 W/m^2 and 716 W/m^2 at 12:00 pm at the surface of solar panel and at the horizontal surface respectively. The average solar intensity measured during daylight hours was 706 and 567 W/m^2 at the surface of solar panel and horizontal surface respectively. The solar intensity at the panel surface was always greater than the horizontal surface due to inclination.

The voltage (V_{oc}) and current (I_{sc}) of battery and inverter were measured at 10:00 am, 12:00 pm, 2:00 pm and 4:00 pm respectively to test the solar PV system performance. The maximum voltage and current of battery were found to be 30.76 V and 15.11 A , while the same for inverter were 31.5 V and 15.56 A respectively at 12:00 pm (Fig 4.2).

Average daily solar intensity (W/m^2) and daily average inverter power (W) were calculated using equation (3.8). The average value of PV system power measured at battery terminal was found to be 387.1 W at 10:00 am. This value was increased to 420.2 W at 12:00 pm and then decreased to 398 W at 2:00 pm and then 313.7 W at 4:00

pm due to decreasing solar radiation as the evening approached (Fig.4.3). The total energy per day (from 10:00 am to 4:00 pm), given by PV modules to the battery bank was 2.4 kWh (taking 400 W average power during 6 light hours). From the load data, consumption of energy per day was observed as 2.212 kWh, which was about 92.16 % of the power supplied by solar PV system.

These results show that PV system would be suitable to supply electricity to cover the load demand without utilizing energy from the electrical grid during the sunny days.

4.2 Effect of pad material and pad area on evaporative cooling at no-load

The ECSS was tested with three different pad materials and four distinctive pad areas at no load condition. The temperature and relative humidity values were determined for outside and inside storage atmosphere simultaneously, while the wet bulb temperature values were obtained from psychrometric chart.

4.2.1 Effect of different pad area and pad material on temperature and relative humidity

The temperature and relative humidity were recorded for inside and outside the ECSS with different type of evaporative cooling pads and pad areas at different ambient conditions. Each of the experiments was started at 10 am and further readings were taken at 1 pm and 4 pm (Fig.4.4-4.7).

The ambient air-dry bulb temperature was 29.5 – 41.1°C with the average being 35.6°C and the ambient relative humidity was 19 – 50% with the average being 32% during the 12 days of experiment.

The temperature and RH profile indicated that higher the RH of the ambient condition less was the cooling effect in cool chamber. At 10:00 am, the dry bulb temperature difference between ambient and storage structure was low because of high RH while the difference increased at 4:00 pm because of reduction in RH value.

The temperature inside the ECSS reduced and there was also an increment in RH value, while the values fluctuated and did not follow any definite pattern under ambient conditions. Temperature and RH difference between ambient and ECSS condition increased with increasing the pad area. The maximum difference in RH and dry bulb

temperature between ambient and inside the cooler was 59% and 14.6°C (Fig. 4.7) respectively when CELdek pad was used on four sides in the ECSS.

4.2.2 Effect of different pad area and pad material on the air cooling efficiency

The cooling efficiency at 10:00 am, 1:00 pm and 4:00 pm was calculated using the equation (3.9). The effect of pad materials and their varying areas on cooling efficiency inside the ECSS were analysed (Fig. 4.8).

The analysis of variance of the results showed there was a significant difference ($P = 0.05$) in cooling efficiency between the three types of evaporative cooling pad materials and four distinctive pad areas (Table 4.1). Using pad only on one side in ECSS gave the least value of cooling efficiency in each of the pad material.

Table 4.1 ANOVA

Source	DF	Sum of squares	Mean Square	F Value	Pr > F
Replication	8	3596.84786	449.60598	8.49	<.0001
Pad material	2	2770.56420	1385.28210	26.17	<.0001
Pad area	3	17878.61732	5959.53911	112.59	<.0001
Error	94	4975.49334	52.93078		
Corrected total	107	29221.52272			

Table 4.2 Cooling efficiency with different pad area

Pad area	Mean
1 side (2.25 m ²)	40.216 ^d
2 sides (4.5 m ²)	52.180 ^c
3 sides (6.75 m ²)	64.262 ^b
4 sides (9 m ²)	74.522 ^a

*Means with the different letter are significantly different

According to the effect of the pad area on the air cooling efficiency of pad materials shows that there was significant difference on cooling efficiency of ECSS (Table 4.2). The pad area listed from the average highest efficiency to the lowest as

Four sides^a > three sides^b > two sides^c > one side^d

Table 4.3 Cooling efficiency with different pad materials

Pad material	Mean
Wood wool pad	53.160 ^b
Khas pad	55.384 ^b
CELdek pad	64.842 ^a

*Means with the different letter are significantly different

According to the effect of the pad materials on the air cooling efficiency of pad materials shows that there was significant difference on cooling efficiency of ECSS (Table 4.3). The pads listed from the average highest efficiency to the lowest as

$$\text{CELdek pad}^a > \text{wood wool pad}^b = \text{khas pad}^b$$

Table 4.4 Effectiveness data of the evaporative cooler

Pad material	Pad area	Temperature drop		Mean cooling efficiency (η %)
		Maximum ($^{\circ}\text{C}$)	Minimum ($^{\circ}\text{C}$)	
Wood wool pad	1 side (2.25 m ²)	6.8	2.5	31.81
	2 sides (4.5 m ²)	5.2	4.4	43.66
	3 sides (6.75 m ²)	11.6	5.5	63.81
	4 sides (9 m ²)	13.8	8.8	73.82
Khas pad	1 side (2.25 m ²)	7.2	4.2	38.91
	2 sides (4.5 m ²)	8.6	3.8	50.25
	3 sides (6.75 m ²)	12.1	7	62.56
	4 sides (9 m ²)	10.5	7.2	70.75
CELdek pad	1 side (2.25 m ²)	11.1	3.8	50.68
	2 sides (4.5 m ²)	10.6	4.2	62.60
	3 sides (6.75 m ²)	13	7.2	67.40
	4 sides (9 m ²)	14.5	8.9	78.67

Average cooling efficiency and maximum and minimum temperature drop was determined during the operating period for different pad materials with various pad areas (Table 4.4). The 50 mm CELdek pad has the highest cooling efficiency 81.79% at 4:00 pm when pad was used on four sides in ECSS while the cooling efficiency was found to be minimum 23.67% when wood wool pad was used only at one side in storage structure.

4.2.3 Suitable pad material and pad area for the cooling system

It was expected that an evaporative cooling system must have decreased the air temperature to the desired degree with minimum power consumption and expenses. An ideal pad media should have the highest air cooling efficiency. The result indicated the ECSS covered with commercial cellulose pads (CELdek) media from all the four sides as the most suitable. So, it was further used for testing under load condition.

4.3 Effect of evaporative cooling on produce

In the experiment, the efficacy of ECSS to keep the fruit and vegetables in good storage condition was evaluated and was compared with room (ambient condition) storage. During the course of storage, change in physiological loss in weight, change in firmness and colour properties were analyzed. Temperature and relative humidity of ECSS, as well as for the condition outside the ECSS was measured, at 9:00 am to 8:00 pm at one hour interval each during storage of produce (Fig. 4.9 and 4.10).

It shows that the temperature and relative humidity values remains almost constant in ECSS throughout the day despite changes in temperature and relative humidity values outside the ECSS.

4.3.1 Physiological loss in weight

The total weight of fruits and vegetables decreased due to physiological stress when stored for long period. The weight of the fruits and vegetables were recorded before keeping them in storing units. After storage, changes in weight were noted on 2nd, 3rd, 4th, 5th and 6th days, respectively (Fig. 4.11).

After 6 days of storage in ECSS, PLW was 23.50% for pointed gourd, 13.15% for cucumber, 9.23% for capsicum, 7.76% for bottle gourd, 3.69% for tomato and 9.59% for papaya while after 3 days storage in ECSS, PLW was 14.92% for spinach and

14.69% for green beans. But in room storage of 6 days, the PLW was 66.3% for pointed gourd, 27.86% for cucumber, 18.58% for capsicum, 13.47% for bottle gourd, 10.62% for tomato and 18.57% for papaya while after 3 days storage in ECSS, PLW was 32% for spinach and 36.75% for green beans.

The analysis of variance of the results showed there was a significant difference ($P = 0.05$) in PLW (%) between the ECSS and in room storage (Table 4.5). It was found that difference in initial and final PLW of produce was highest in case of room storage in each of the fruits and vegetables while the low difference was found in ECSS.

Table 4.5 Effect of ECSS on PLW (%)

S.No.	Produce	Storage	Mean PLW (%)	Pr>F
1	Pointed gourd	Room	29.449 ^b	.0011
		ECSS	13.385 ^a	
2	Cucumber	Room	14.948 ^b	<.0001
		ECSS	8.022 ^a	
3	Capsicum	Room	9.754 ^b	<.0001
		ECSS	4.909 ^a	
4	Bottle gourd	Room	8.305 ^b	<.0001
		ECSS	4.267 ^a	
5	Tomato	Room	5.023 ^b	<.0001
		ECSS	1.836 ^a	
6	Spinach	Room	16.764 ^a	0.0006
		ECSS	7.278 ^b	
7	Green beans	Room	17.425 ^a	0.0024
		ECSS	7.398 ^b	
8	papaya	Room	10.089 ^a	<.0001
		ECSS	4.868 ^b	

*Means with the different letter are significantly different

4.3.2 Change in firmness

The change in firmness is associated with the stage of maturity. The firmness of fruits and vegetables decreased when stored for longer period. The firmness of fruits and

vegetables was recorded before keeping them in storing units. Initially the firmness values were 14.71N for pointed gourd, 13.01N for cucumber, 11.21N for capsicum, 13.08N for bottle gourd, 7.82N for tomato and 6.78N for papaya (Fig 4.12).

After storage, change in firmness was noted on 2nd, 3rd, 4th, 5th and 6th days, respectively. After 6 days of storage in ECSS firmness was 10.51 N for pointed gourd, 10.06N for cucumber, 6.44N for capsicum, 10.11N for bottle gourd, 4.52N for tomato and 2.58N for papaya in ECSS. But in room storage of 6 days, the firmness was 8.86N for pointed gourd, 7.58N for cucumber, 3.45N for capsicum, 8.12N for bottle gourd, 2.81N for tomato and 1.43N for papaya.

The analysis of variance of the results showed there was a significant difference ($P = 0.05$) in firmness (N) between the ECSS and in room storage (Table 4.6). It was found that difference in initial and final firmness of produce was found to be highest in case of room storage in each of the fruits and vegetables while the low difference was found in ECSS.

Table 4.6 Effect of ECSS on Firmness (%)

S.No.	Produce	Storage	Mean firmness (N)	Pr>F
1	Pointed gourd	ECSS	12.5458 ^a	0.0118
		Room	11.4584 ^b	
2	Cucumber	ECSS	11.8564 ^a	0.0001
		Room	10.1808 ^b	
3	Capsicum	ECSS	8.9641 ^a	< 0.0001
		Room	6.5447 ^b	
4	Bottle gourd	ECSS	11.9368 ^a	0.0001
		Room	10.6071 ^b	
5	Tomato	ECSS	6.5126 ^a	0.0001
		Room	5.3884 ^b	
6	papaya	ECSS	4.7962 ^a	< 0.0001
		Room	3.8182 ^b	

*Means with the different letter are significantly different

4.3.3 Change in colour

The change in colour is also associated with the stage of maturity. It decreased when stored for longer period. The colour of fruits and vegetables was recorded before keeping them in storing units.

The pointed gourd, cucumber, bottle gourd and tomato shown marginal increases in L* and b* value because of appearance of yellowness in most of the vegetables and marginally decrease in a* value because of reduction in green colour. But for the spinach and capsicum (Table 4.7), reduction in L* and b* value was observed because of appearance of darkness in the surface of the vegetables but a* value was found to be increased in the spinach while reduced in capsicum because of presence of red spot on the surface. The change in L*, a* and b* values from the initial values had lesser difference when stored in ECSS but had higher difference from initial value when stored in room condition.

Table 4.7 Effect of ECSS on colour

S. No.	Produce	Storage	Before storage			After storage		
			L*	a*	b*	L*	a*	b*
1	Pointed gourd	ECSS	32.38	-7.22	19.22	40.67	-6.15	22.2
		Room				42.97	-4.44	25.28
2	Cucumber	ECSS	62.52	-8.09	27.35	63.10	-7.59	31.13
		Room				65.73	-7.57	32.68
3	Bottle gourd	ECSS	66.32	-9.45	36.61	65.58	-7.89	28.73
		Room				63.84	-7.42	29.17
4	Tomato	ECSS	35.09	28.97	38.56	38.55	17.45	23.41
		Room				42.71	20.49	24.50
5	Spinach	ECSS	52.45	-7.64	23.42	45.72	-7.90	23.17
		Room				42.77	-8.31	22.57
6	Capsicum	ECSS	33.34	-7.51	24.86	31.17	-6.79	15.22
		Room				30.04	-6.46	12.67

4.3.4 Shelf life of fruits and vegetables

Shelf life of fruits and vegetables was decided on the basis of change of physiological loss in weight during storage in ECSS and in room condition. The weight of the produce after each day of storage was estimated and compared with their initial weight. The difference in the weight was estimated by storing the produce both in the storage structure and in the room (ambient condition). When the collected produce loses more than 10% of its fresh weight, it starts to wilt and soon gets unusable. Shelf life of different fruits and vegetables was determined during experiment as shown in Table 4.8.

**Table 4.8 Change in Shelf-life (in days) of fruits and vegetables
when stored in ECSS and in room**

S.No.	Produce	Shelf-life (day)	
		In ECSS	In room condition
1	Spinach	3	2
2	Green beans	3	2
3	Pointed gourd	3	2
4	Cucumber	5	3
5	Capsicum	7*	4
6	Bottle gourd	8*	4
7	Tomato	13*	6
8	Papaya	7*	4

*days calculated from regression analysis as PLW (%) measured only till 6th day of storage

Following chapter deals with the detailed discussion on various results obtained from the present study.

5.1 Performance of Solar PV system

The results of the suitability of solar PV system to provide electricity to the evaporative cooled storage structure as shown in section 4.1. At 12 pm solar intensity (W/m^2) was remain maximum irrespective of tilt and horizontal position of solar panel (Fig. 4.1). Since at 12 pm the sun becomes normal to the earth surface therefore the solar radiation is normal to the horizontal and tilt surface of the solar panel which result maximum intensity.

The solar intensity directly affects the solar PV system's battery and inverter voltage/current. As explained above the panel receives maximum intensity of solar radiation during noon therefore inverter voltage/current and battery voltage/current is maximum at 12 pm. The graph shows gradual increase in voltage and current up to 12 pm and gradually decreased after that due to decrease in the intensity of solar radiation as the evening approached (Fig 4.2).

We know that $P = VI$; therefore shows the same trend as shown by voltage and current because of effect of solar intensity on power of the solar PV system (Fig. 4.3).

5.2 Effect of pad material with various pad area on evaporative cooling at no-load

A study was conducted to determine the effect of pad area (4 levels) and pad materials (3 levels) on relative humidity and temperature as shown in section 4.2.1. There were changes in ambient and storage relative humidity/temperature with respect to change in pad area and pad materials in ECSS (Fig. 4.4-4.7). The graphs in section 4.2.1 clearly indicates that the difference between ambient and storage temperature increased with increase in the pad area irrespective of pad material. The reason for the above trend is that as the pad area increased the rate of heat transfer also increases due to increased area available for the heat transfer.

The results of ANOVA (Table 4.1) indicated that there was significance difference among the treatments. The individual effect of the variables viz., pad area and pad material on air cooling efficiency was significant at 5% level of probability. The maximum air cooling efficiency revealed by the evaporative cooled storage structure when was covered from all sides (Table 4.2). It might be due to the fact that with increase in heat transfer area the difference between ambient and storage temperature increases which results in elevated air cooling efficiency.

There was influence of pad materials on air cooling efficiency (Table 4.3). It is evident from the results that the CELdek pad material gave maximum performance due to uniform thickness and particle size distribution throughout the surface area.

From the results of ANOVA (Table 4.1) it is desired to use CELdek pad material as it gives desired degree of power consumption, expenses and highest air cooling efficiency. The result indicated the ECSS covered with commercial cellulose pads (CELdek) media from all the four sides as the most suitable. So, it was further used for testing under load condition.

5.3 Effect of evaporative cooling on produce

The statistical analysis of the data taken during 6 days was performed to find the significance of the variables viz., developed storage structure and ambient condition on physiological loss in weight at 5% level of probability. The results of ANOVA indicated that there was significance difference among the treatments (Table 4.5). It was found that difference in initial and final PLW of produce was found to be highest in case of room storage in each of the fruits and vegetables while the low difference was found in ECSS (Fig. 4.11). This might be due to the fact that fruits and vegetables require low temperature and high humidity to increase their shelf life. The graphs clearly indicates that when the fruits and vegetables were stored in ECSS compared to room storage PLW was minimum due to low temperature and high relative humidity (Fig. 4.9 and 4.10). Therefore the developed evaporative cooled storage structure provides ideal condition for storage of fruits and vegetables in the long run.

The statistical analysis of the data taken during 6 days was performed to find the significance of the variables viz., developed storage structure and ambient condition on firmness at 5% level of probability. The results of ANOVA indicated that there was significance difference among the treatments (Table 4.6). It was found that difference in initial and final firmness of produce was found to be highest in case of room storage in each of the fruits and vegetables while the low difference was found in ECSS (Fig. 4.12). This might be due to the fact that fruits and vegetables require low temperature and high humidity to increase their shelf life. The graphs clearly shows that when the fruits and vegetables were stored in ECSS compared to room storage firmness was maximum due to low temperature and high relative humidity. Therefore the developed evaporative cooled storage structure provides ideal condition for storage of fruits and vegetables storage for a short time.

The change in colour is also associated with the stage of maturity and decreased when stored for longer period. The color of fruits and vegetables was recorded before keeping them in storing units. Since the storage period was 6 days therefore no significant difference was found in the stored produce with respect to the room storage and ECSS.

Change in Shelf-life (in days) of fruits and vegetables when stored in ECSS and in room storage results clearly indicates that the shelf life of all the fruits and vegetables increased by more than two days when it was stored in ECSS compared to stored in room condition (Table 4.8).

Energy is vital input for sustainable and economic development of any nation. With the economic development, the demand of energy is expanding in almost every sector. There is an intense deficiency of electricity in rural areas particularly in remote villages. The solar photovoltaic (SPV) technology offers tremendous capability of harnessing a portion of solar energy due to its inherent advantages such as easy and silent conversion into electricity using solar cells.

Storage assumes an important part in handling of horticultural produce since it is constantly subjected to spoilage due to different endogenous and exogenous factors. Because of inadequate storage facilities to hold the produce safe for longer periods, prices plunge at harvest time and large quantities are spoiled before they could be disposed off.

The ECSS was designed, fabricated and tested in the Division of Agricultural Engineering at IARI, New Delhi. The chamber requires a small electrical energy for operation of fan and pump so 4 SPV panels each of 100 W_p were used to obtain the desired power. Two battery of 12 V each were used to store the power generated by the PV array during the day time to meet load requirements at night time and an inverter of 1250 VA was used to convert the DC generated by SPV system into AC to operate the fan and pump.

A 1 m³ storage capacity storage structure (dimensions of about 1.8 m length X 1.5 m width X 1.6 m height) with 30 cm high trapezium roof was fabricated. For insulating the structure from the top it was covered with the corrugated asbestos sheet. It was provided with the exhaust fan at the top to control the relative humidity and reduce CO₂ concentration released by stored fruits and vegetables inside the chambers. It also circulates the air and helps to maintain homogenizes temperature and relative humidity inside ECSS. A water pump of 40 l/min and 500 l water tank were used for the recirculation of water and storage of receiving sump water respectively.

The SPV system for cooling an ECSS was installed and tested. The electric fan and water pump for cooling in ECSS were operated with energy generated through SPV system. The power output of the panel was measured. It was also observed that the load

current is directly proportional to the insolation. The study shows that the PV system was running satisfactorily. As PV system are clean and do not cause pollution of any type during their use while the price of PV system decreases every year and their efficiencies and reliability increased, there is a good scope of the practical utilization of this research findings.

ECSS was tested with three different pad materials and four distinctive pad areas for selection of the suitable material. The cooling performance was evaluated in the following terms; temperature, relative humidity and cooling efficiency inside the ECSS and at ambient condition respectively.

There was a significance difference in cooling efficiency between three types of cooling pad materials (CELdek pad, wood wool pad and khas pad) and four distinctive pad areas (2.25 m^2 , 4.5 m^2 , 6.75 m^2 and 9 m^2). The commercial cellulose pads (CELdek) when used at four sides shown the highest air cooling efficiency (approximately 80%) for 50mm pad thickness. When these values taken into consideration CELdek was found as the best pad material characteristics compared to the other two local alternative pad materials (khas and wood wool pads).

For testing the ECSS low shelf life produce were selected, these were as follows; spinach, green beans, pointed gourd, cucumber, bottle gourd, capsicum, tomato and papaya. Measurement of physiological loss in weight (PLW, %) and change in firmness (N) each day of storage and colour at first and last day of storage were used to evaluate the shelf life of fruits and vegetables.

There was significant difference in PLW (%) and firmness values of the fruits and vegetables stored in ECSS and in room (ambient condition). The shelf life calculated for the different fruits and vegetables when stored in ECSS increased by around 1-3 days compared to room storage.

Evaporative cooling system could be more efficient for the storage of fruits and vegetables where the climate is hot and dry likewise can be used under other climate condition. It has low cost of manufacturing, negligible operational cost and is better than mechanical refrigeration. So the ECSS can be used in any place where cold storage facility is not available. Evaporative cooling system is easy to operate, efficient and affordable most especially for the farmers in developing nations.

ABSTRACT

Solar Energy is one of the main source of the renewable energy. Solar photovoltaic power (SPV) is used today in numerous applications. For this investigation the SPV system consists of 4 solar panels of $100W_p$ each, one inverter and a battery bank (including 2 batteries). The total energy per day given by PV modules to the battery bank was 2.4 kWh. From the load data, consumption of energy was observed 2.212 kWh per day which was about 92.16 % of the power supplied by solar PV system. These results showed that SPV system is suitable to supply electricity to cover the loads requirement without utilizing power from the electrical grid during the sunny day.

An evaporative cooled storage structure (ECSS) was designed to assess the performance with three different pad materials and four distinctive pad areas in no load condition. The materials examined were wood wool, khas and CELdek. The areas for the cooling system considered were of $2.25m^2$, $4.5m^2$, $6.75m^2$ and $9m^2$. The performance criteria included measuring temperature, relative humidity and cooling efficiency. The analysis of variance of the results showed that there was a significant difference ($P=0.05$) in cooling efficiency between the three types of evaporative cooling pad materials and four distinctive pad areas. The results showed that under the no-load condition, the average air cooling efficiency was highest for CELdek at 78.67%, compared to 73.82% for wood wool and 70.75% for khas pad material when these materials were used in all sides four in the ECSS.

For testing the performance of the ECSS produce having low shelf life such as spinach, green beans, pointed gourd, cucumber, bottle gourd, capsicum, tomato and papaya were used. The results obtained for fruits and vegetables storage indicates that there was significant difference in PLW (%) and firmness values of the fruits and vegetables when stored in ECSS than those in room (ambient condition). The shelf life for the fruits and vegetables stored in ECSS was 1-3 days more compared to room storage. Evaporative cooling system is easy to operate, efficient and affordable most especially for the farmers in developing nations in areas where there is no electricity available or its supply is erratic since it is operated on solar energy and does not require conventional electricity.

अक्षय ऊर्जा स्रोतों में सौर ऊर्जा एक मुख्य स्रोत है। सौर फोटोवोल्टिक (एस०पी०वी०) पैनल आज कई अनुप्रयोगों में उपयोग किये जाते हैं। इस प्रयोग के लिए एस०पी०वी० प्रणाली में ४ सौर पैनल प्रत्येक १०० वाट, एक इनवर्टर और एक बैटरी बैंक (२ बैटरी सहित) सम्मिलित थे। प्राप्त परिणाम दिखाते हैं कि इन्वर्टर से अधिकतम शक्ति १२:०० बजे मिली जो कि ४५६ वाट थी। मॉड्यूल द्वारा प्रति दिन बैटरी बैंक को दी गई कुल ऊर्जा २.४ किलोवाट घंटा थी। भार आंकड़ों से, प्रति दिन ऊर्जा की खपत २.२१२ किलोवाट घंटा प्राप्त की गई जो कि सौर पीवी प्रणाली द्वारा आपूर्ति की शक्ति का ६२.१६% थी। प्राप्त परिणाम प्रदर्शित करते हैं कि धूप वाले दिन के दौरान एसपीवी प्रणाली बिना विद्युत ग्रिड उपयोग के मांगो की आपूर्ति के लिए उपयुक्त है।

खाद्य सामग्री डाले बिना तीन अलग अलग पैड सामग्री और चार विशिष्ट पैड क्षेत्रों के प्रदर्शन के आकलन के लिए एक वाष्पीकृत शीत भंडारण गृह का निर्माण किया गया। जांच की सामग्री में लकड़ी की छाल, खस और सेलडेक के पैड लिए गये। शीतलन प्रणाली के लिए २.२५, ४.५, ६.७५ और ९ वर्गमीटर के क्षेत्रफल लिए गए। मापदंड प्रदर्शन को मापने के लिए तापमान, सापेक्षिक आर्द्रता और शीतलन दक्षता सम्मिलित थे। परिणामों की भिन्नता के विश्लेषण ने प्रदर्शित किया कि तीन अलग अलग वाष्पीकृत शीतलन पैड सामग्री और चार विशिष्ट पैड क्षेत्रों की शीतलन दक्षता में एक सार्थक अंतर ($P=0.05$) था। भार रहित स्थिति में प्राप्त परिणामों ने दिखाया कि जब पैड सामग्रियों को वाष्पीकृत शीत भंडारण गृह में सभी तरफ उपयोग में लिया गया तब औसत शीतलन दक्षता लकड़ी की छाल के लिए ७३.८२%, खस पैड सामग्री के लिए ७०.७५% और सेलडेक के लिए ७८.६७% पाई गई जो कि सभी में अधिकतम थी।

वाष्पीकृत शीत भंडारण गृह के प्रदर्शन के परीक्षण के लिए कम जीवनावधि वाले फल और सब्जियों जैसे पालक, हरी फलियां, परवल, लोकी, ककड़ी, शिमला मिर्च, टमाटर और पपीता उपयोग किये गये। फलों और सब्जियों के भंडारण से प्राप्त परिणाम दर्शाते हैं कि वाष्पीकृत शीत भंडारण गृह और कमरे (परिवेश स्थिति) में संग्रहित फल और सब्जियों के शारीरिक भार में कमी (%) और दृढ़ता मूल्यों में सार्थक अंतर था। वाष्पीकृत शीत भंडार गृह में संग्रहित फल और सब्जियों की जीवनावधि कमरे की तुलना में १ से ३ दिन अधिक थी। वाष्पीकृत शीतलन प्रणाली सौर ऊर्जा पर संचालित है और पारंपरिक बिजली की आवश्यकता नहीं है इसलिये यह विशेष रूप से विकासशील देशों में उन क्षेत्रों के किसानों के लिए जहाँ बिजली उपलब्ध नहीं है, संचालित करने के लिए आसान, कुशल और लागत प्रभावी है।

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Table A.1 Performance of SPV system during summer of 2015 on typical clear sunny days at 10:00 am

Date	Battery		Inverter		Solar intensity(W/m^2)	
	Voltage (V)	Current (Amps)	Voltage (V)	Current (Amps)	Tilt surface	Hori. surface
8-apr	28.26	13.72	28.38	14.53	692	668
15-apr	28.28	13.89	30.54	15.06	732	618
17-apr	25.52	13.14	26.35	12.54	702	571
18-apr	28.19	13.52	28.37	14.27	708	675
19-apr	28.74	13.68	29.4	14.19	711	706
20-apr	26.57	12.49	27.59	13.42	806	769
21-apr	26.59	13.05	28.03	13.46	765	743
22-apr	26.53	14.44	30.35	15.02	897	682
23-apr	29.27	14.39	30.19	14.92	883	875
24-apr	29.96	14.56	30.79	15.21	860	653
25-apr	29.51	14.47	30.31	14.92	718	611
26-apr	28.97	14.36	30.32	15.09	703	615
Average	28.033	13.809	29.218	14.385	764.75	682.166
St.dev.	1.406	0.669	1.433	0.8459	76.668	83.201
C.V., %	5.015	4.842	4.905	5.880	10.025	12.196

Table A.2 Performance of SPV system during summer of 2015 on typical clear sunny days at 12:00 pm

Date	Battery		Inverter		Solar intensity (W/m^2)	
	Voltage (V)	Current (Amps)	Voltage (V)	Current (Amps)	Tilt surface	Hori. surface
8-apr	30.58	14.53	31.52	15.42	809	769
15-apr	30.56	14.32	31.35	15.27	820	532
17-apr	30.27	14.28	31.34	15.47	913	836
18-apr	30.52	15.11	31.5	15.56	925	724
19-apr	30.52	15.11	31.5	15.56	925	724
20-apr	30.76	14.46	30.97	15.43	852	811
21-apr	27.18	13.23	28.13	13.77	884	785
22-apr	27.86	14.74	30.44	15.3	1070	842
23-apr	27.86	14.38	30.59	15.12	982	808
24-apr	30.04	14.8	30.94	15.32	980	775
25-apr	29.56	14.35	30.38	15.34	897	712
26-apr	29.56	14.35	30.38	15.34	897	712
Average	29.606	14.47	30.753	15.242	912.83	752.5
St.dev.	1.260	0.49	0.943	0.48	73.066	83.582
C.V., %	4.258	3.384	3.065	3.148	8.004	11.11

Table A.3 Performance of SPV system during summer of 2015 on typical clear sunny days at 2:00 pm

Date	Battery		Inverter		Solar intensity (W/m ²)	
	Voltage (V)	Current (Amps)	Voltage (V)	Current (Amps)	Tilt surface	Hori. surface
8-apr	28.24	14.63	28.94	15.21	950	591
15-apr	26.9	12.2	27.74	13.56	828	540
17-apr	29.95	14.48	30.99	15.24	764	635
18-apr	30.27	15.02	31.34	15.53	748	708
19-apr	30.27	15.02	31.34	15.53	748	708
20-apr	30.13	14.37	29.26	15.07	795	764
21-apr	28.06	13.77	28.39	14.39	872	644
22-apr	27.51	14.07	28.33	14.48	892	579
23-apr	27.51	14.1	30.49	15.14	864	618
24-apr	28.55	14.15	29.4	14.58	557	449
25-apr	28.75	14.72	30.53	15.16	738	598
26-apr	28.75	14.72	30.53	15.16	738	598
Average	28.740	14.27	29.77	14.920	791.16	619.33
St.dev.	1.177	0.758	1.253	0.568	101.60	83.21
C.V., %	4.095	5.316	4.209	3.811	12.842	13.43

Table A.4 Performance of SPV system during summer of 2015 on typical clear sunny days at 4:00 pm

Date	Battery		Inverter		Solar intensity (W/m ²)	
	Voltage (V)	Current (Amps)	Voltage (V)	Current (Amps)	Tilt surface	Hori. surface
8-apr	24.92	14.53	31.52	15.42	809	769
15-apr	30.56	14.32	31.35	15.27	820	532
17-apr	30.27	14.28	31.34	15.47	913	836
18-apr	30.52	15.11	31.5	15.56	925	724
19-apr	30.52	15.11	31.5	15.56	925	724
20-apr	30.76	14.46	30.97	15.43	852	811
21-apr	27.18	13.23	28.13	13.77	884	785
22-apr	27.86	14.74	30.44	15.3	1070	842
23-apr	27.86	14.38	30.59	15.12	982	808
24-apr	30.04	14.8	30.94	15.32	980	775
25-apr	29.56	14.35	30.38	15.34	897	712
26-apr	29.56	14.35	30.38	15.34	897	712
Average	29.605	14.47	30.75	15.242	912.83	752.5
St.dev.	1.26	0.49	0.942	0.479	73.06	83.582
C.V., %	4.257	3.383	3.064	3.148	8.004	11.107

Table B.1 Hourly variation in ambient and inside condition for ECSS during summer 2015 when wood wool pad was used

Pad area	Time (h)	Rep.	Outside		WBT(°C)	Inside		Sat. η (%)
			DBT(°C)	RH(%)		DBT(°C)	RH(%)	
1 side (2.25m ²) 18-april	10:00 am	1	32.8	42	22	30.2	56	24.074
		2	33.2	45	23.5	31.3	57	19.587
		3	33.5	41	22.9	30.6	56	27.358
	1:00 pm	1	34.3	38	22.9	32	54	20.175
		2	37.1	32	23.4	33	51	29.927
		3	36.9	31	23	33.3	51	25.899
	4:00 pm	1	37.3	27	22.2	30.5	58	45.033
		2	37.1	26	21.8	30.2	60	45.098
		3	36.8	26	21.7	30	58.7	45.033
2 side (4.5m ²) 8-april	10:00 am	1	29.9	44	20.7	25.2	66	51.086
		2	29.5	48	21.2	25	72	54.216
		3	31.4	41	21.2	26.4	62	49.019
	1:00 pm	1	32.6	38	21.6	27.6	60	45.454
		2	33.4	35	21.5	28.2	56	43.697
		3	35.2	33	22.3	29.6	52	43.410
	4:00 pm	1	33.6	35	21.6	29.9	48	30.833
		2	34.1	31	21.1	28.9	50	40
		3	33.8	32	21.3	29.4	49	35.2
3 Side (6.75m ²) 21-april	10:00 am	1	32.6	38	21.8	27.3	62	49.074
		2	32.7	42	22.5	27.9	63	47.058
		3	34.5	36	22.5	28.2	62	52.5
	1:00 pm	1	35.4	35	23	27.6	68	62.903
		2	36	32	22.7	27.2	68	66.165
		3	36.5	29	22.3	26.9	69	67.605
	4:00 pm	1	37.1	27	22.2	25.5	83	77.852
		2	36.3	24	20.8	24.7	75	74.838
		3	36	25	20.8	24.4	78	76.315
4 side (9 m ²) 24-april	10:00 am	1	33.5	32	20.8	24.7	59	69.291
		2	33.8	35	21.8	25.6	62	68.333
		3	36.7	32	23.2	27.2	60	70.370
	1:00 pm	1	38.4	30	23.8	27	65	72.382
		2	39.5	28	24	27.3	69	78.709
		3	40	23	22.9	26.7	63	77.777
	4:00 pm	1	41.1	21	22.9	27.2	72	76.373
		2	40.2	20	22	26.5	68	75.274
		3	40.1	20	21.9	26.3	70	75.824

**Table B.2 Hourly variation in ambient and inside condition for ECSS during
summer 2015 when khas pad was used**

Pad area	Time (h)	Rep.	Outside		WBT(°C)	Inside		Sat. η (%)
			DBT(°C)	RH(%)		DBT(°C)	RH(%)	
1 side (2.25 m ²) 19-april	10:00 am	1	32.4	39	21.8	28.1	58	40.566
		2	32.5	44	22.8	29.1	60	35.051
		3	33.6	37	22.1	28.5	59	44.347
	1:00 pm	1	34.5	32	21.6	29.9	56	35.658
		2	34.7	28	20.7	30.8	51	27.857
		3	35.1	27	20.7	30.6	50	31.25
	4:00 pm	1	36.4	24	20.8	29.7	49	42.948
		2	37.1	22	20.7	29.3	46	47.560
		3	36.5	23	20.5	29.3	47	45
2 side (4.5 m ²) 15-april	10:00 am	1	31	40	22.1	28.8	56	36.190
		2	32.6	43	22.6	29.4	56	32
		3	33.7	39	22.6	29.3	57	39.639
	1:00 pm	1	32.9	41	22.4	28	62	46.666
		2	33.5	39	22.4	27.7	64	52.252
		3	34.1	34	21.8	28.2	58	47.967
	4:00 pm	1	35.2	31	21.8	27.3	62	58.955
		2	35.4	28	21.2	26.2	64	64.788
		3	35.2	29	21.4	26.6	63	62.318
3 Side (6.75 m ²) 23-april	10:00 am	1	34.3	33	21.5	27.2	62	55.468
		2	34.2	34	21.8	27.5	63	54.032
		3	35.7	33	22.7	28.4	62	56.153
	1:00 pm	1	36.1	28	21.7	28.1	57	55.555
		2	36.7	26	21.6	28.1	57	56.953
		3	38.6	25	22.5	27.8	64	67.080
	4:00 pm	1	39.7	24	23	26.8	73	77.245
		2	37.5	22	20.9	26.2	62	68.072
		3	37.9	22.3	21.2	25.8	67	72.455
4 side (9 m ²) 26-april	10:00 am	1	32	41	21.5	24.8	71.8	68.571
		2	32.1	45	21.9	25.6	74	63.725
		3	33.4	39	22.5	25.5	71	72.477
	1:00 pm	1	34.3	35	22.4	25.2	76	71.129
		2	35.1	34	22.6	25.4	80	77.6
		3	35.7	32	21.8	26.2	69	68.345
	4:00 pm	1	36.2	28	21.8	25.5	67	74.305
		2	35.4	25	20.5	25.1	56	69.127
		3	35.3	25.9	20.6	24.8	60.7	71.428

Table B.3 Hourly variation ambient and inside condition for ECSS during summer 2015 when CELdek pad were used

Pad area	Time (h)	Rep.	Outside		WBT(°C)	Inside		Sat. η (%)
			DBT(°C)	RH(%)		DBT(°C)	RH(%)	
1 side (2.25 m ²) 20-april	10:00 am	1	32.6	40	22.1	28.8	56	36.190
		2	32.6	43	22.6	29.4	56	32
		3	33.7	39	22.6	29.3	57	39.639
	1:00 pm	1	34.7	35	22.4	29.5	55	42.276
		2	36.2	32	22.8	29.3	58	51.492
		3	38.4	28	23.3	29.2	61	60.927
	4:00 pm	1	41	24	23.8	29.5	62	66.860
		2	40.2	23	23	29.5	58	62.20
		3	40.4	23.3	23.2	29.3	60	64.534
2 side (4.5 m ²) 17-april	10:00 am	1	30.1	49	21.9	25.9	75	51.219
		2	30.2	50	22.1	26.3	74	48.148
		3	31.4	49	22.9	26.7	77	55.294
	1:00 pm	1	35.1	32	22	26.9	68	62.595
		2	35.4	32	22.2	27.6	64	59.090
		3	36.1	31	22.5	27.3	67	64.705
	4:00 pm	1	37	30	22.9	26.5	74	74.468
		2	36.4	28	21.9	25.7	71	73.79
		3	36.5	29	22.2	25.9	72	74.125
3 Side (6.75 m ²) 22-april	10:00 am	1	34	33	21.5	26.9	64	56.8
		2	34.1	35	22	27.1	68	57.851
		3	35.6	32	22.4	28.2	61	56.060
	1:00 pm	1	35.7	28	21.4	26.6	63	63.636
		2	36.1	27	21.4	26.8	62	63.265
		3	37.3	24	21.4	26.2	66	69.811
	4:00 pm	1	38.4	22	21.6	25	77	79.76
		2	36.5	21	20.55	23.8	81	79.623
		3	36.7	21	20.4	23.7	78	79.75
4 side (9 m ²) 25-april	10:00 am	1	34.8	38	23.3	25.9	76	77.39
		2	35.1	46	25.1	27.6	79	75
		3	35.6	32	22.5	25.4	75	77.862
	1:00 pm	1	37.3	29	22.9	26.6	74	74.305
		2	37.9	28	23	26.3	70	77.852
		3	39.2	26	23.4	26.5	79	80.379
	4:00 pm	1	40.3	22	22.9	25.7	81	83.908
		2	39.7	19	21.6	25.3	76	79.558
		3	39.5	20	21.8	25	78	81.92

Table C.1 Daily changes in PLW (%) inside and outside ECSS during storage

Nature of storage	Samples	Weight changes (gm) during storage intervals (days)						Final PLW (%)
		1 st day	2 nd day	3 rd day	4 th day	5 th day	6 th day	
ECSS	Spinach	244.3	226.8 (7.163)	207.9 (14.92)	167 (31.65)	-	-	14.921*
	Green beans	245.2	226.3 (7.707)	209.3 (14.66)	173.6 (29.20)	-	-	14.668*
	Pointed guard	151.3	143 (5.478)	131.8 (12.88)	122.7 (18.90)	119.6 (20.9)	115.7 (23.5)	23.504
	Cucumber	194.1	183.6 (5.41)	178.6 (7.99)	175.7 (9.47)	170.8 (11.9)	168.6 (13.1)	13.147
	Capsicum	187.1	183 (2.184)	180.8 (3.381)	174.6 (6.681)	172.4 (7.84)	169.7 (9.29)	9.296
	Bottle guard	428.1	417.8 (2.405)	412 (3.756)	407.7 (4.761)	395.2 (7.67)	394.9 (7.76)	7.760
	Tomato	110.1	109.3 (0.726)	108.6 (1.399)	107.4 (2.449)	106.9 (2.81)	106.1 (3.69)	3.688
	Papaya	569.3	557.2 (2.114)	550.2 (3.253)	532.3 (6.493)	523.1 (8.12)	514.8 (9.59)	9.594
Room	Spinach	258.3	210.2 (18.61)	175.6 (32)	-	-	-	32.001*
	Green beans	270.9	228.9 (15.50)	171.4 (36.74)	-	-	-	36.747*
	Pointed guard	231.4	195.5 (15.51)	141.8 (38.72)	111.3 (51.90)	90.4 (60.9)	77.8 (66.3)	66.335
	Cucumber	393.1	365 (7.137)	342.3 (12.92)	317.7 (19.17)	298.7 (24.1)	283.6 (27.9)	27.864
	Capsicum	369.7	355.9 (3.732)	342.1 (7.466)	323.2 (12.57)	306.8 (17.1)	301 (18.6)	18.582
	Bottle guard	389.1	369.3 (5.088)	358.6 (7.838)	347.4 (10.71)	339.1 (12.8)	336.7 (13.4)	13.467
	Tomato	112.1	109.8 (2.051)	107.1 (4.46)	105.9 (5.53)	104.5 (6.67)	100.2 (10.6)	10.615
	Papaya	680.9	654.9 (3.823)	630.4 (7.423)	595.9 (12.48)	564.1 (17.2)	554.4 (18.6)	18.572

Table C.1 Daily changes in firmness (N) inside and outside ECSS during storage

Nature of storage	Samples	Firmness changes (gm) during storage intervals (days)						Firmness drop, N (A-B)
		1 st day (A)	2 nd day	3 rd day	4 th day	5 th day	6 th day (B)	
ECSS	Pointed guard	14.71	14.597	13.557	11.045	10.853	10.51	4.201
	Cucumber	13.017	12.848	12.288	12.155	10.827	10.06	2.952
	Capsicum	11.208	10.98233	10.147	7.88	7.116	6.441	4.766
	Bottle guard	13.08\	12.77267	12.174	12.05	11.418	10.11	2.963
	Tomato	7.828	7.578667	6.979	6.633	5.536	4.519	3.309
	Papaya	6.781	6.409667	5.04	4.417	3.540	2.587	4.193
Room	Pointed guard	14.711	12.83633	11.29	11.11	9.947	8.856	5.855
	Cucumber	13.017	11.406	10.21	9.623	9.237	7.583	5.434
	Capsicum	11.208	7.913667	6.208	5.962	4.231	3.745	7.463
	Bottle guard	13.081	12.21367	11.042	10.237	8.948	8.119	4.962
	Tomato	7.828	7.029	6.306	5.04	3.308	2.81	5.014
	Papaya	6.781	5.386	3.852	3.014	2.441	1.43	5.35



Exhaust fan



Electric board



Thermostat

PVC pipe fitting



5 way fitting



Flow control valve



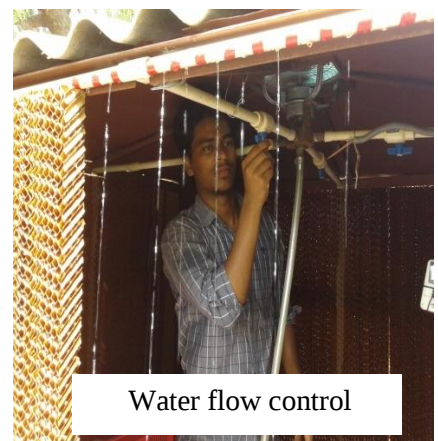
Flexible pipe



Sump tank



Water pump



Water flow control

Plate 3.1 Components of ECSS

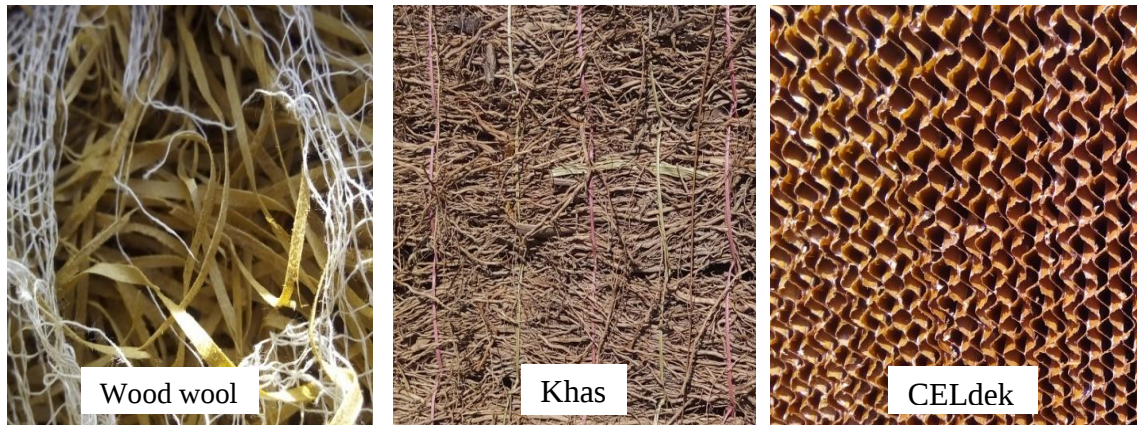


Plate 3.2 Pad materials used



Batteries



Inverter



Plate 3.3 Solar PV system



Pyranometer



Data logger



Hygro-thermometer



Multimeter



Weighing balance (1)



Weighing balance (2)



Colour analyzer (Hunter colour Lab)



Texture analyzer

Plate 3.4 Instrument used for measurement



ECSS frame without



Polythene inside the pad to restrict air flow



Fruits and vegetable storage



Closing the side of ECSS

Plate 3.4 Evaporative cooled storage structure

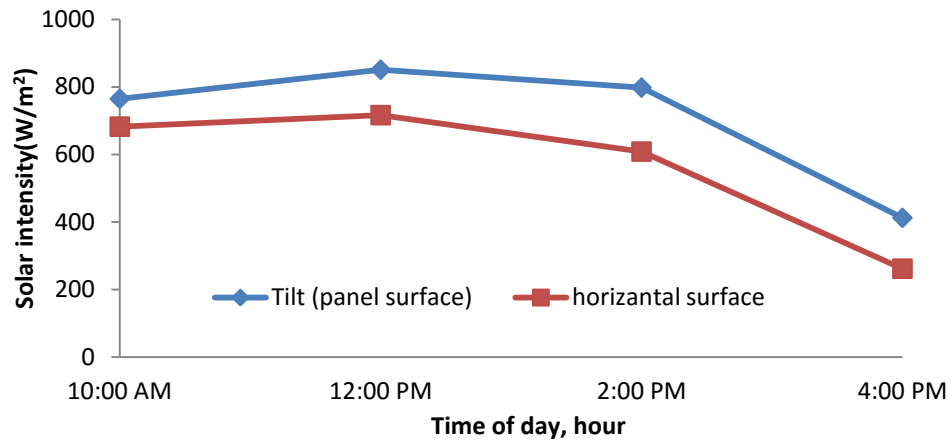


Fig. 4.1 Hourly variation of solar intensity on horizontal surface and at tilt (panel)

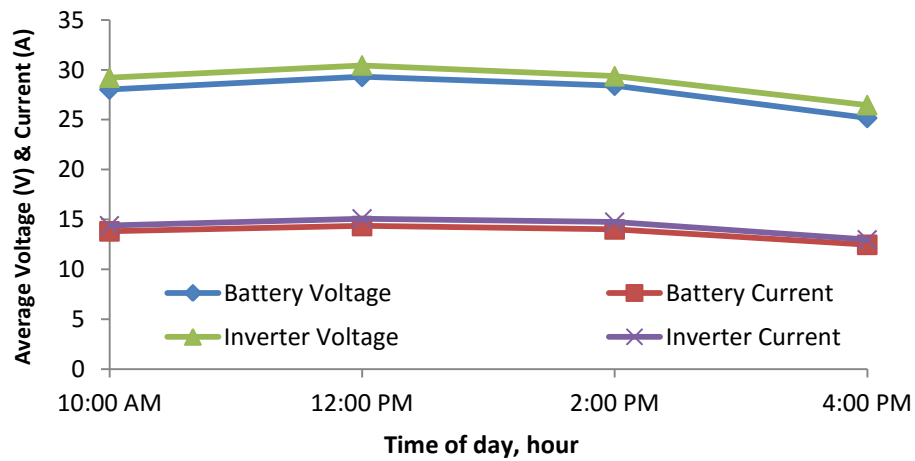


Fig. 4.2 Hourly variation of voltage and current

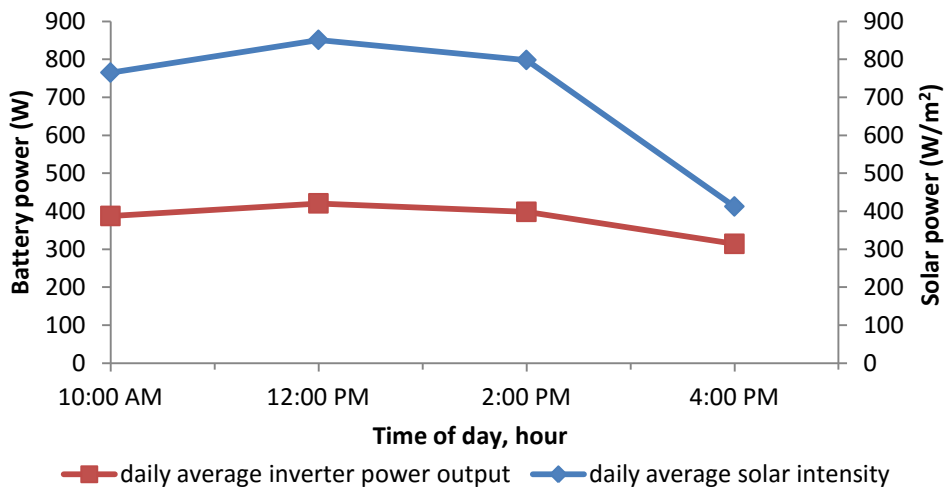


Fig. 4.3 Hourly variation of solar intensity and Solar PV system power

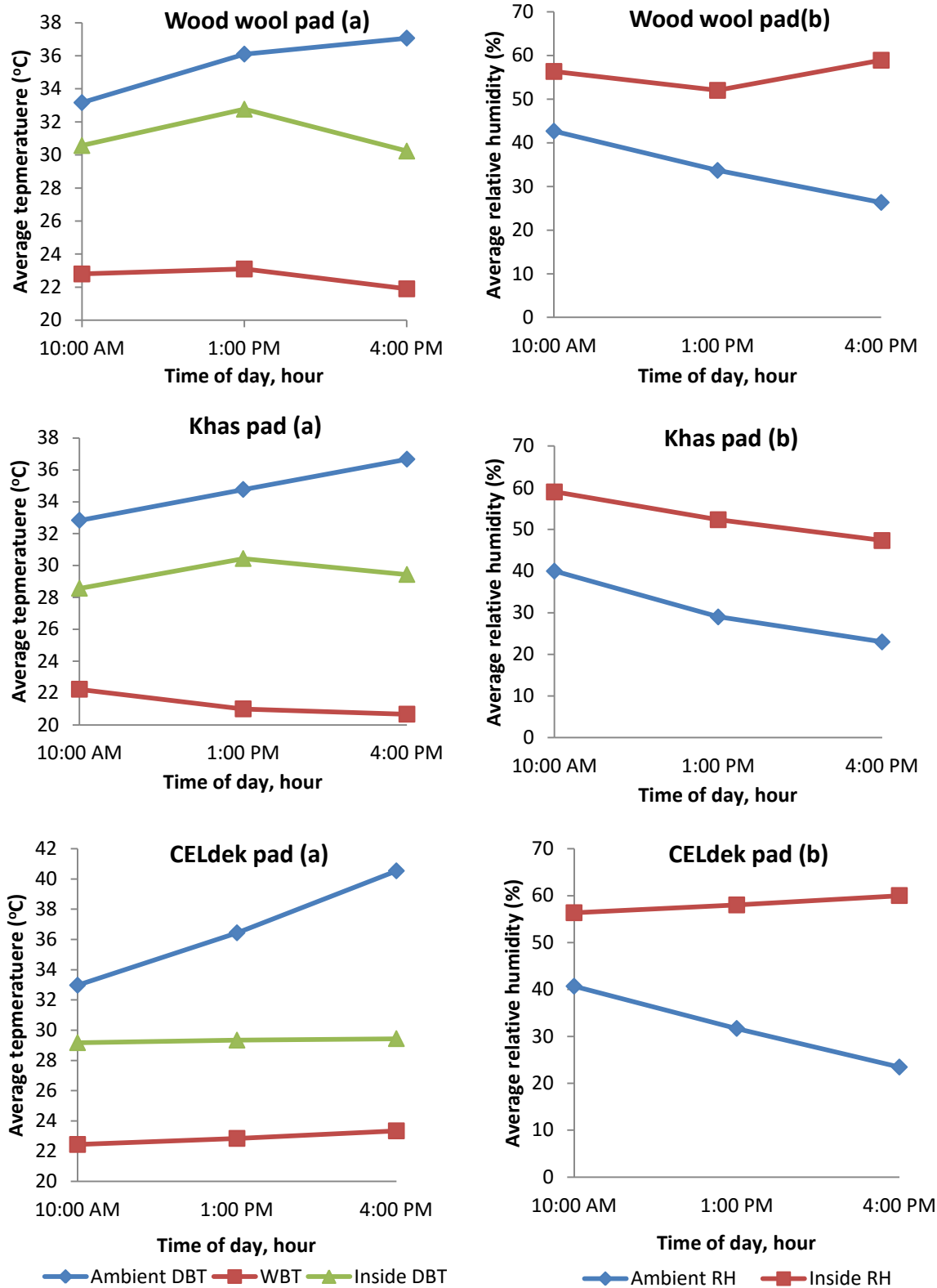


Fig. 4.4 Hourly variation of temperature (a) and relative humidity (b) for ambient and inside the ECSS when pad was used only at one sides

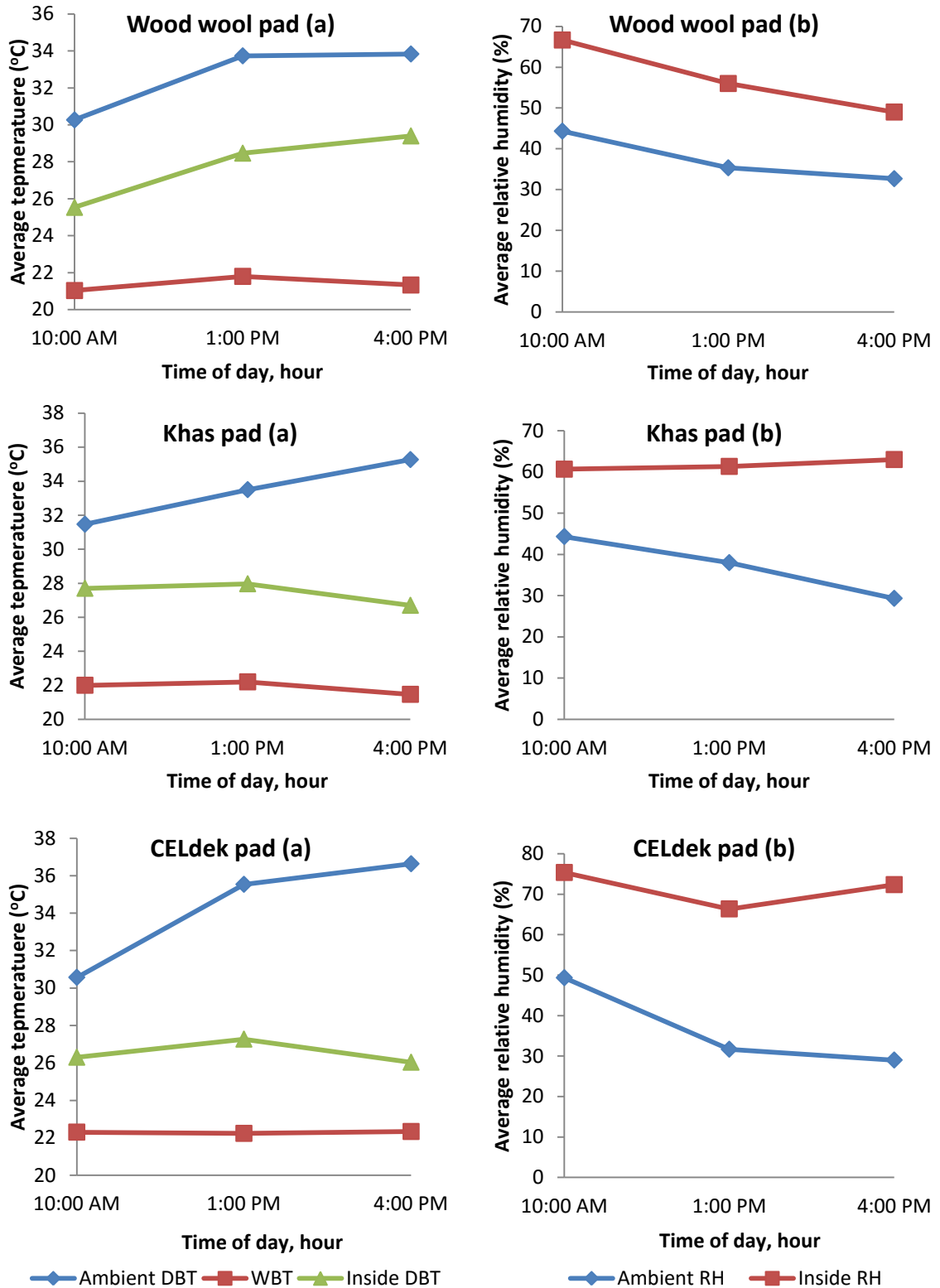


Fig. 4.5 Hourly variation of temperature (a) and relative humidity (b) for ambient and inside the ECSS when pad was used at two side

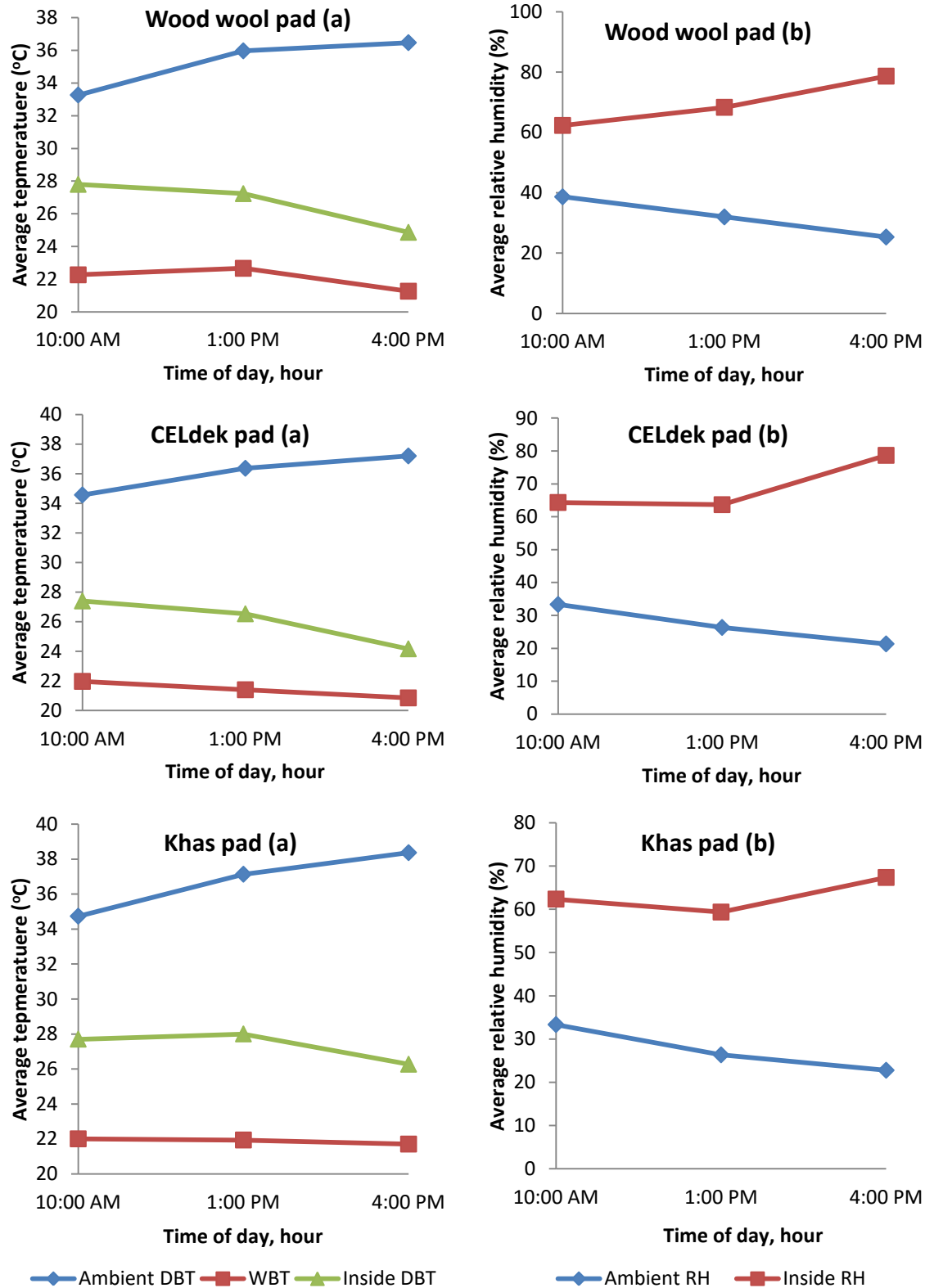


Fig. 4.6 Hourly variation of temperature (a) and relative humidity (b) for ambient and inside the ECSS when pad was used at three sides

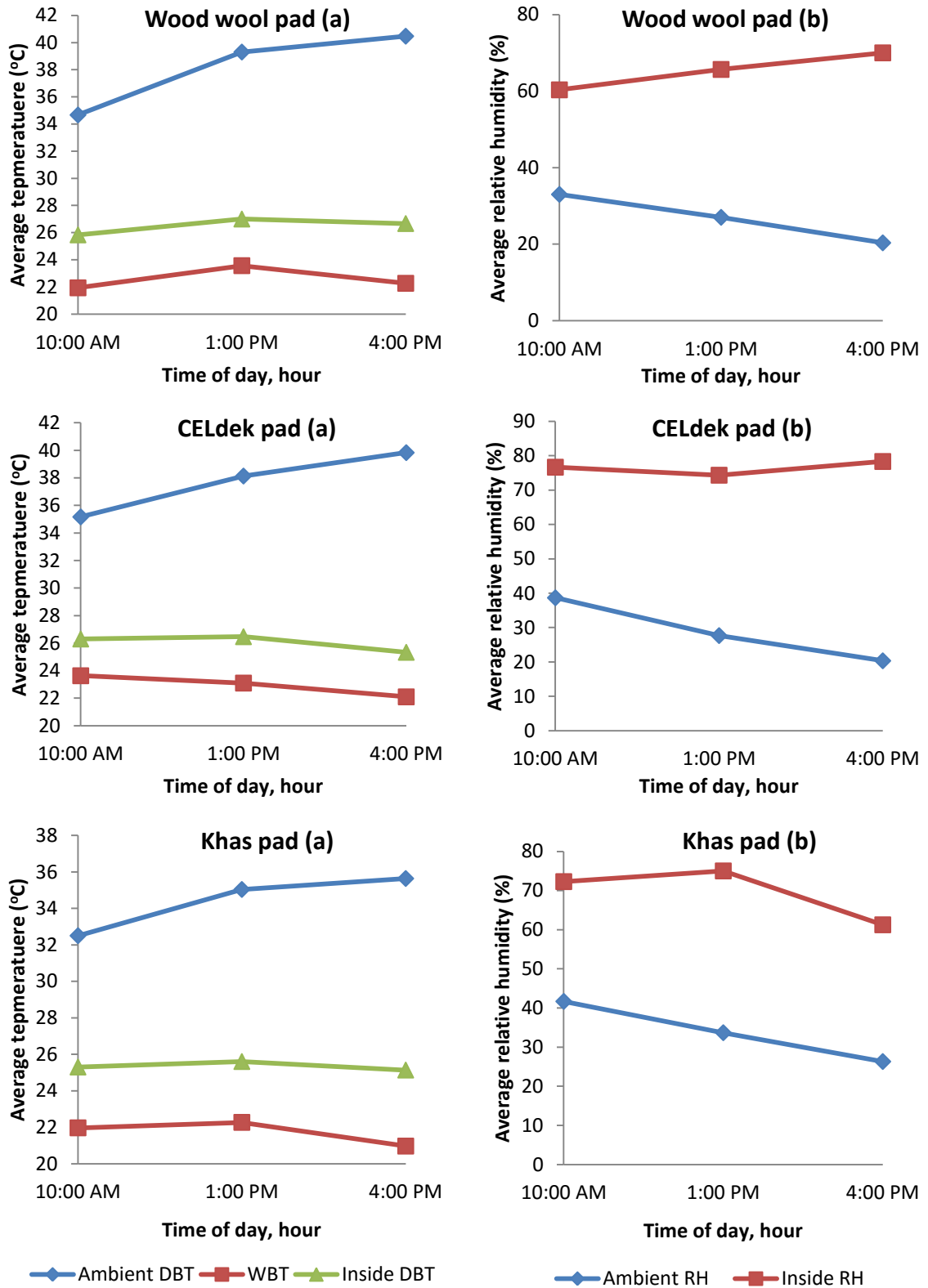


Fig. 4.7 Hourly variation of temperature (a) and relative humidity for ambient and inside the ECSS when pad was used at four sides

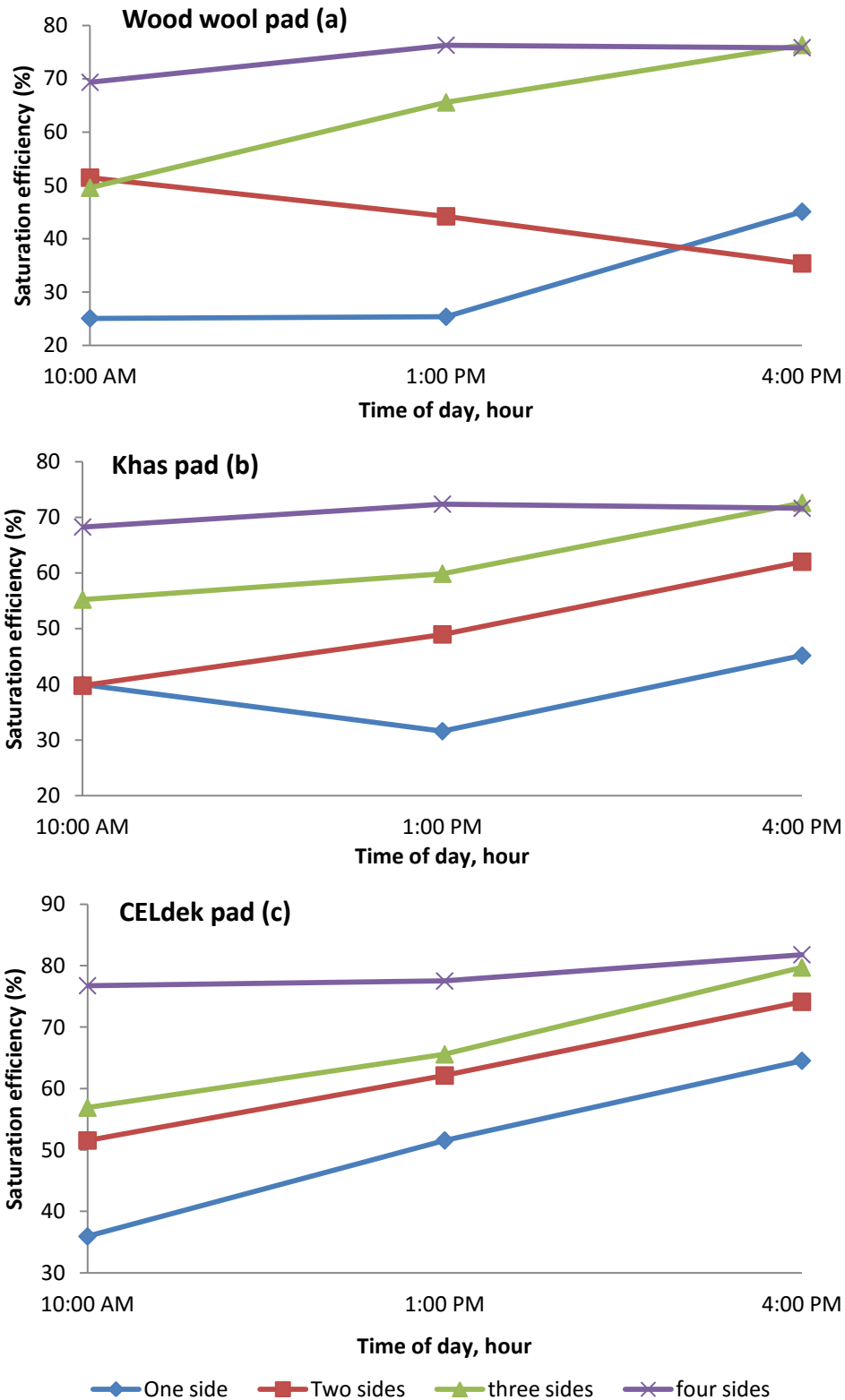


Fig. 4.8 Hourly variation of saturation efficiency for three different pad material (a, b, c) when pad used one, two, three and four side in each of the material

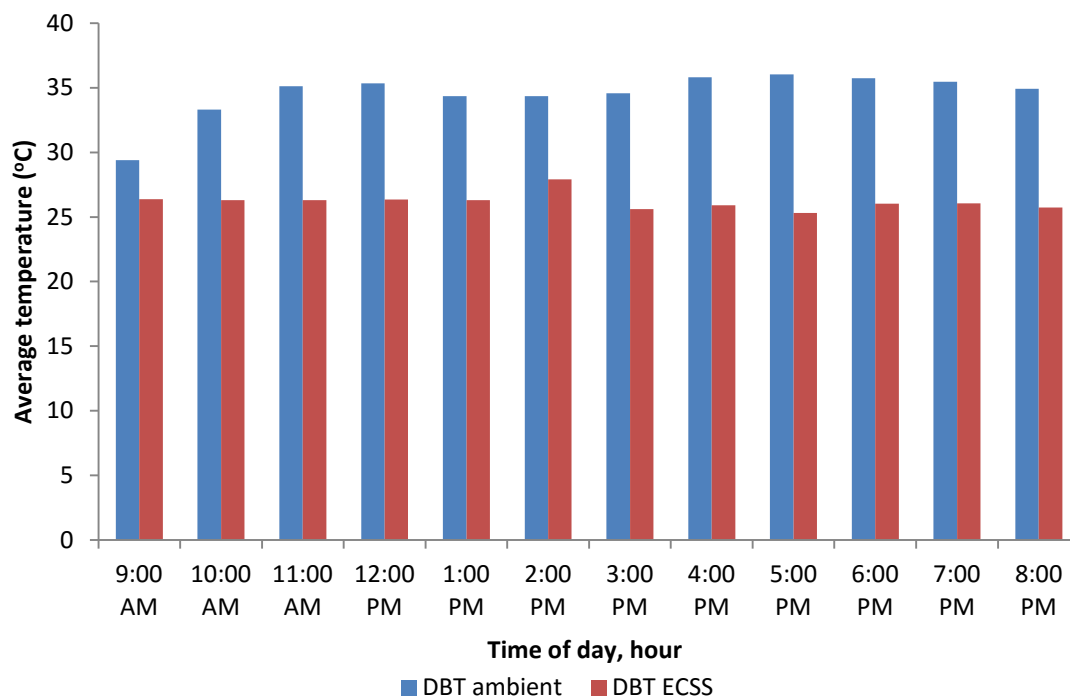


Fig.4.9 Hourly variation in average temperature (°C) during storage of fruits and vegetables in ambient and in ECSS

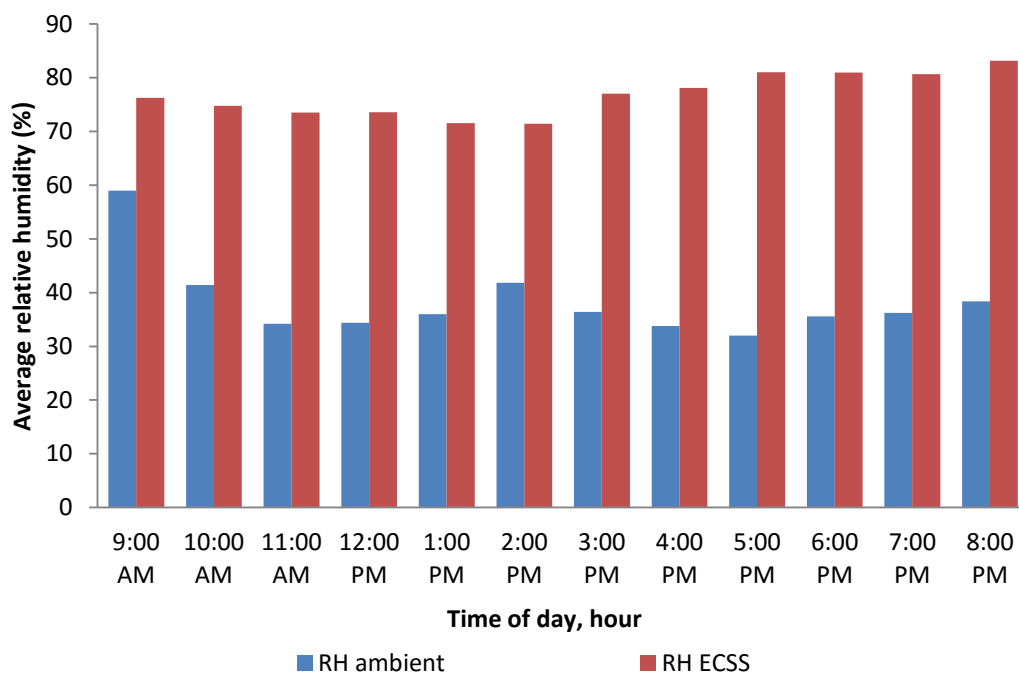


Fig.4.10 Hourly variation in relative humidity (%) during storage of fruits and vegetables in ambient and in ECSS

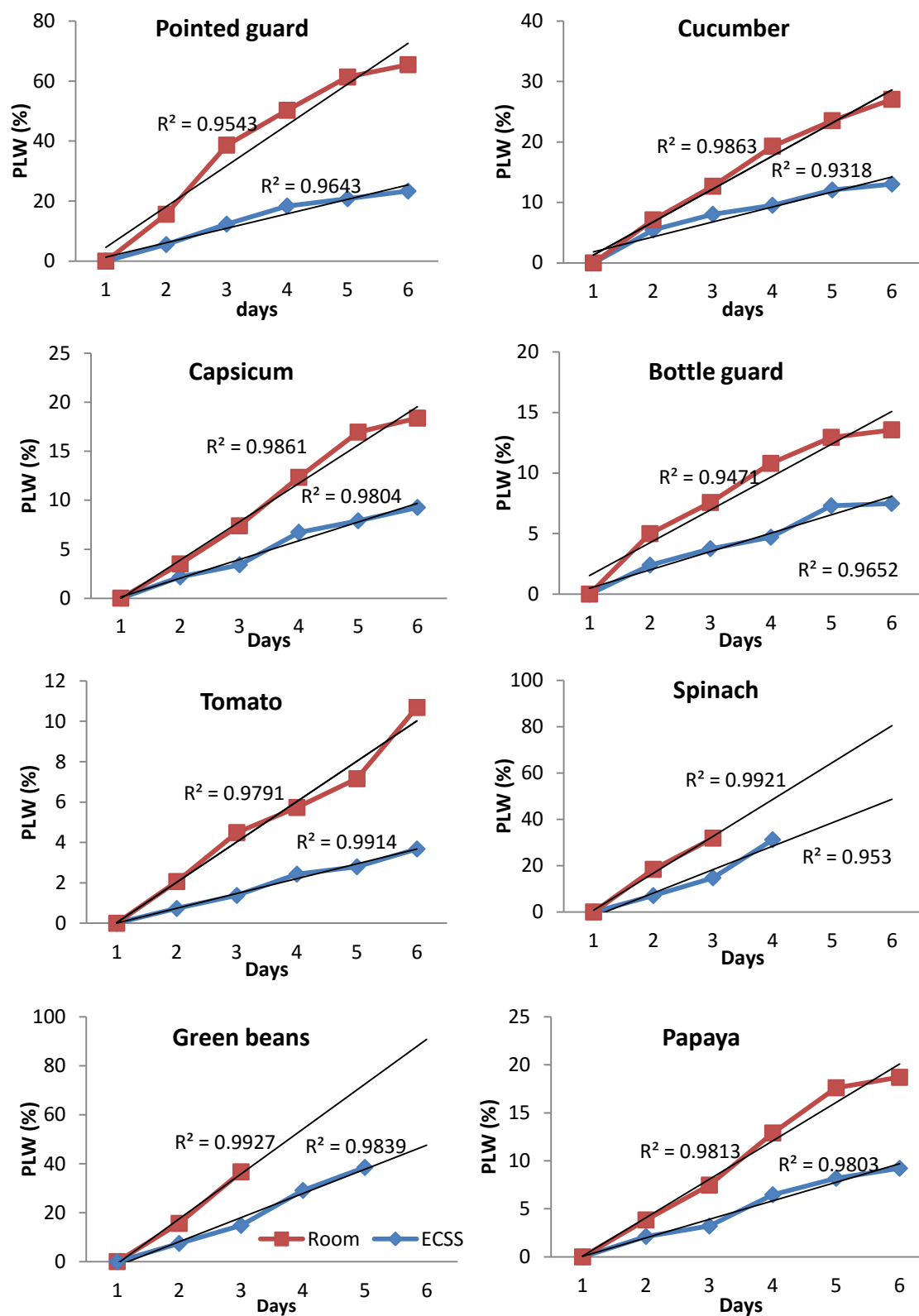


Fig.4.11 Changes in PLW (%) of different fruits and vegetables during storage

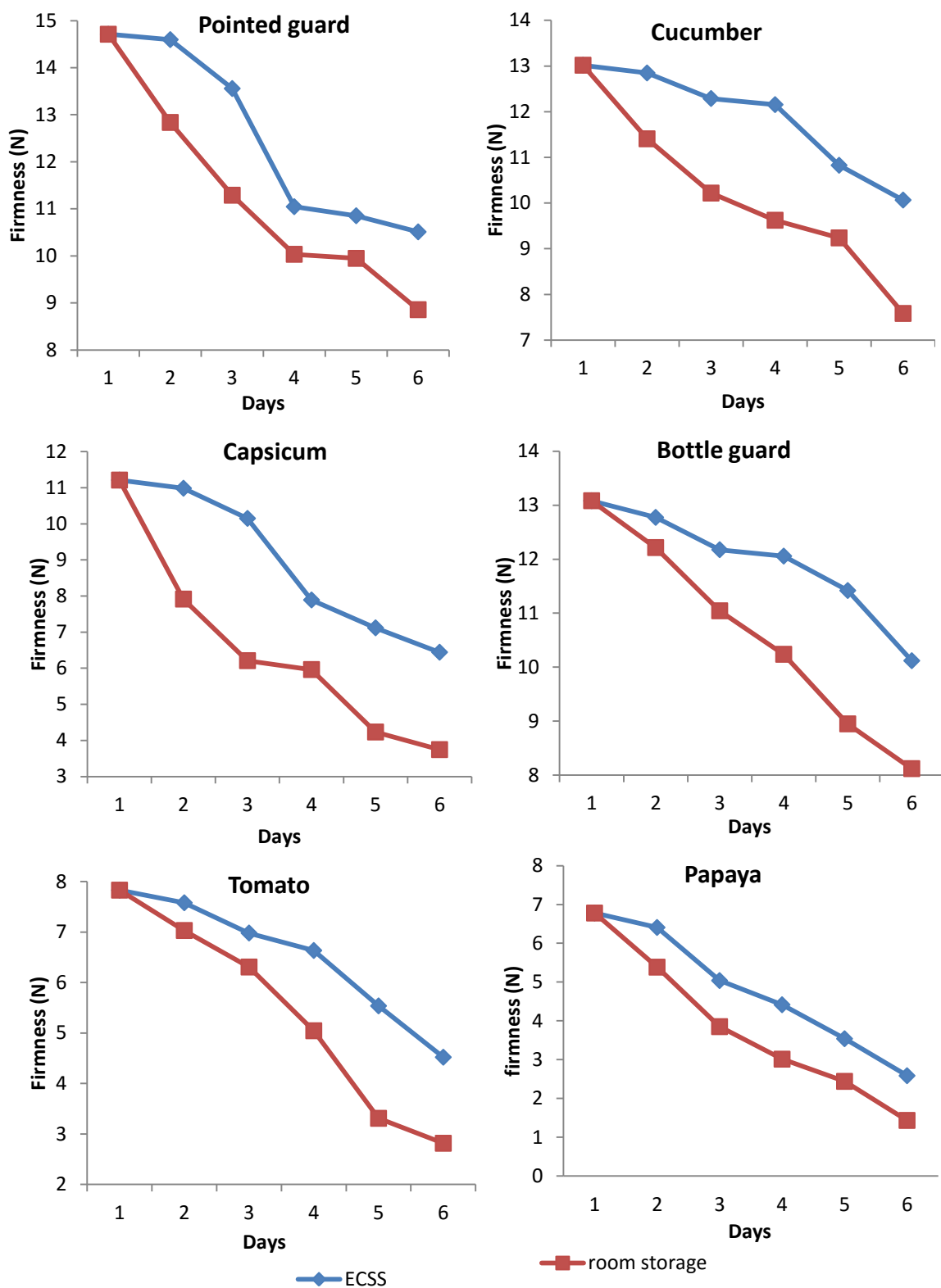


Fig.4.12 Changes in Firmness (N) of different fruits and vegetables during storage